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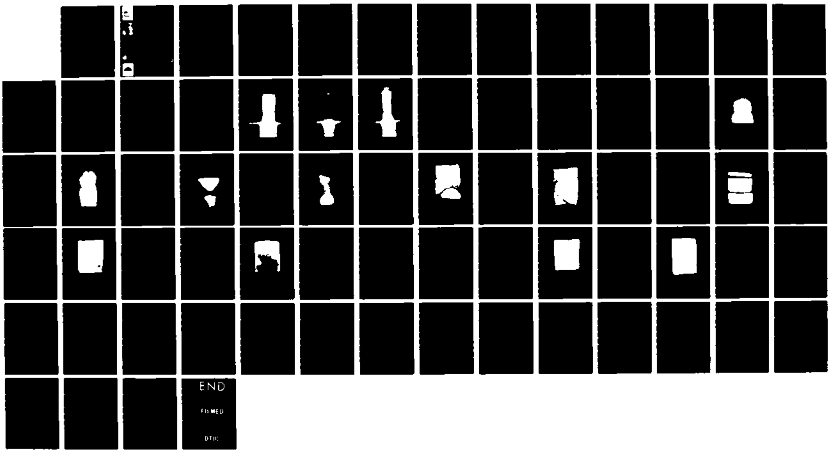

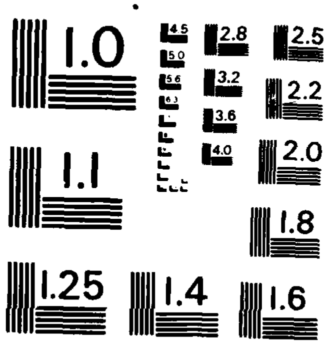

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USE OF X-RAY RADIOGRAPHIC TECHNIQUES IN THE EVALUATION OF SOIL LINERS

by

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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

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A preliminary study was undertaken to determine the usefulness of soil X-ray radiographic techniques and radio-opaque permeants in testing compacted clay liners used for waste containment. Two methods of using X-ray techniques were examined: one method involved intermittent examination of a test cell during permeation; a second method involved preparing X-radiographs of whole or sliced specimens of simulated liners after they had been subjected to permeameter testing.

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20. ABSTRACT (Continued).

X-radiographs taken during permeation of a bentonite/sand liner permitted documentation of the progressive invasion of the liner and the development of changes in liner structure (formation of channels or voids). A radio-opaque permeant ($Pb(NO_3)_2$) proved useful for following liquid movement, but was not necessary if only structural changes in the liner were being investigated.

X-radiographs prepared from whole or sliced samples of simulated liners after permeability testing provided data on the homogeneity of the sample, production of open flow paths in the sample, uneven infiltration of the permeating liquid, and the occurrence of surface plugging from suspended solids and side wall leakage. Precipitates forming in the liner could also be observed. The X-ray technique was evaluated with four different types of compacted clay soil liners and five permeating liquids--three aqueous solutions and two suspensions in organic solvents. The radio-opaque compounds used as tracers were $Pb(NO_3)_2$, $Pb(C_2H_3O_2)_2$, and Pb_3O_4.

Using soil X-ray techniques to follow fluid movement during permeability testing or using X-rays to examine soil samples after permeability testing allows the investigator to check the uniformity of test samples and the performance of the test equipment and to obtain a better understanding of liner/liquid interactions. A thorough testing program can combine both X-ray examination during and after testing.

Further research in this area should include comparison of the performance of permeability test apparatus and development of techniques for the examination of samples of liner material or slurry wall collected by coring field installations. X-ray techniques should also be adapted to examine the effects of chemically reactive liners. Development of organic solvent-based radio-opaque tracers would allow expanded testing of liner/organic waste interaction.

PREFACE

This project was supported as an In-House Laboratory Independent Research (ILIR) Project under Project No. 4A161102A91D, Task Area 02, Work Unit 154.

This report was prepared by Dr. Philip G. Malone of the Site Characterization Unit (SCU) and Mr. James H. May, Chief, SCU, Engineering Geology Applications Group (EGAG), Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES) and Dr. Kirk W. Brown and Mr. James C. Thomas of the Soil and Crop Sciences Department, Texas A&M University. Texas A&M University performed all of the permeability testing, under Purchase Order No. DACA39-84-M-1064. X-ray radiographs were prepared by Mr. Thomas Harmon of the SCU. Mr. Scott Murrell, SCU, assisted in the preparation of photos and drawings. The X-ray diffraction analysis was performed by Mr. J. Pete Burkes, Mmes. Elizabeth E. Odell, Joyce C. Ahlvin and Mr. G. S. Wong of Structures Laboratory. Immediate supervisor on the project was Mr. John H. Shamburger, Chief, EGAG. General supervision was provided by Dr. Don C. Banks, Chief, EGRMD, and Dr. William F. Marcuson III, Chief, GL.

During the preparation of this report, COL Tilford C. Creel, CE, and COL Robert C. Lee, CE, were Commanders and Directors of WES; Mr. F. R. Brown was Technical Director. At the time of publication, COL Allen F. Grum, USA, was Director of WES; Dr. Robert W. Whalin was Technical Director.

CONTENTS

USE OF X-RAY RADIOGRAPHIC TECHNIQUES IN THE EVALUATION OF SOIL LINERS

PART I: INTRODUCTION

Background

1. Compacted or amended soils have been widely employed as containment barriers in the storage, treatment or disposal of a wide variety of liquids or leachates from solids (US EPA 1983). In cases where a impounded liquid is a threat to the quality of local ground water (for example, salt water or sewage), the integrity of the liner has been a major consideration in impoundment design. Modern solid waste landfills do not accept liquid wastes, but the liner requirements are often a major engineering concern because precipitation percolating through the landfill cap and contacting the waste can become contaminated and the liner is the principal barrier that prevents the contaminated water from mixing with local ground water.

2. Soils employed in liners may be very slowly permeable when placed, but contact with waste can potentially alter the structure of the compacted soil or change the crystal character of individual mineral components and cause the liner to change permeability (Haxo 1978, Brown and Anderson 1983). Laboratory-scale testing using a variety of liquids as permeants has demonstrated that the permeability changes can result from: (a) solution of mineral particles in the liner; (b) piping of fine particles out of the liner; (c) changes in the structure of the clay liner; (d) changes in the crystal structure of minerals in the liner (Acar, Oliveri, and Field 1984; Anderson and Brown 1981; Anderson, Brown, and Green 1981, 1982; Brown, Thomas, and Green 1984; Evans and Fang 1985; Foreman and Daniel 1984; Daniel 1984; Green, Lee, Jones, and Palit 1983).

3. Slurry walls are similar in purpose and component materials to liners. A slurry wall is a vertical ground water barrier formed by mixing a graded soil in a bentonite slurry-filled trench. The problems of waste/soil interaction are similar for both barriers and liners and testing procedures for clay-soil mixes employed in both structures are identical (Anderson, Crawley, and Zebcik 1984; Anderson and Jones 1983; US EPA 1984).

4. Clay liners and bentonite (clay) slurry walls are the critical

features employed in designing many disposal sites and in developing remedial measures (Pacey and Karpinski 1980, Price and Sommerer 1982, US EPA 1983). Failure of clay liners and slurry walls can result in the loss of wastes to the surrounding soil and loss of time and effort involved in construction of these barriers. The barriers are developed to contain wastes indefinitely and even relatively slow degradation of the barrier is considered a serious problem.

5. Guidance documents on the design of clay liners and soil-bentonite slurry walls recommend laboratory permeameter tests that employ permeants that are similar in composition to the liquids to be retained (US EPA 1983, 1984). Useful test results can be obtained from a variety of permeameter designs, (e.g., fixed wall or triaxial) if careful attention is paid to the test and the quality control procedures followed in the laboratory (US EPA 1984). For example, errors can arise if preparing or packing the sample is not done correctly or if the sample separates from the side wall or if gas bubbles are generated by the interaction of the permeant and the liner material. If the permeant contains suspended material or precipitates, soil clogging will occur and give false readings.

6. X-ray radiography has been used extensively in the study of structures in soil or sediment cores (Krinitzsky 1970). Lamination, varves, cross-bedding as well as rock fragments and fossils produce sufficient differences in density to be imaged by X-rays. The problems of examining invaded liner samples are much the same as those encountered with sediment cores. In liner investigations, however, the permeant can be selected to provide enhanced contrast between the constituents in the clay liner and the invading fluid.

Purpose and Scope

Purpose

7. Testing of soils for landfill liners is generally done by packing soil samples in a permeameter and examining changes in permeability as different fluids are added. The results obtained can be influenced by sample preparation and the significance of a change in permeability is difficult to interpret. The purpose of this research was to explore the use of soil X-radiography in determine what changes are occurring or have occurred that increase or decrease the rate of fluid movement in a compacted soil.

Scope

8. This project evaluates the ability of X-ray radiography to monitor the real-time invasion of a simulated liner by examining the effect of a lead nitrate/nitric acid solution on a simulated liner formed from a mixture of a commercial bentonite and sand. The project also assesses the usefulness of X-radiography in studying the effect of laboratory permeameter testing on specific samples by preparing X-radiographs of samples of four soils each of which had been permeated with one of four simulated waste liquids or a control (0.01 N $CaSO_4$) solution. Three replicates were prepared for each soil/permeant pair. In all, 60 permeated samples were prepared and examined using X-ray techniques.

PART II: TEST METHODS AND MATERIALS

9. To evaluate the ability of X-radiography to follow the movement of a simulated waste into and through a clay layer as permeation occurred, a plastic cell was fabricated and a layer of mixed hydrated bentonite and sand was placed in it. The simulated waste, an acidic lead nitrate solution, was permitted to infiltrate the bentonite/sand layer from above. In a second sequence of tests X-ray radiographs were prepared from soil samples that had been tested using standard permeameter techniques, in order to learn if the radiographs could be used to determine the type of interaction occurring between the soil and the permeant.

Real-time Liner Tests

Test cell design

10. A test cell was fabricated from 75-mm (3-inch) ID, schedule 40 polyvinyl chloride (PVC) pipe to hold a 100-mm (4-inch) thick layer of simulated liner made by mixing sand and a commercially prepared bentonite. The test cell consisted of a 320-mm long section of pipe glued to a coupling with a screw-type clean-out plug installed in the bottom. A hole was drilled in the clean-out plug and a pipe nipple was screwed through the hole to provide a drain. A length of flexible PVC tubing attached to the pipe nipple carried the drainage into a plastic reservoir that could hold all of the liquid permeant. A cut-away drawing of the test cell is shown in Figure 1.

Simulated clay liner

11. A simulated liner was prepared by mixing one part bentonite clay (Aquagel, Baroid Petroleum Services of NL Industries, Houston, Tex.) with four parts by volume of coarse filter sand. The sand and bentonite were throughly mixed in a dry condition, then water was added until the bentonite was completely hydrated. The wet mix slowly settled and was allowed to stand in contact with water for 24 hours.

12. The bottom of the test cell was packed with dacron filter floss and a 100-mm thick layer of clean filter sand was placed over the dacron filter. Excess water was decanted from the hydrated bentonite/sand mix and a 100-mm thick layer was poured into the test cell over the clean sand layer. Clean water was placed on top of the bentonite/sand layer and allowed to stand for

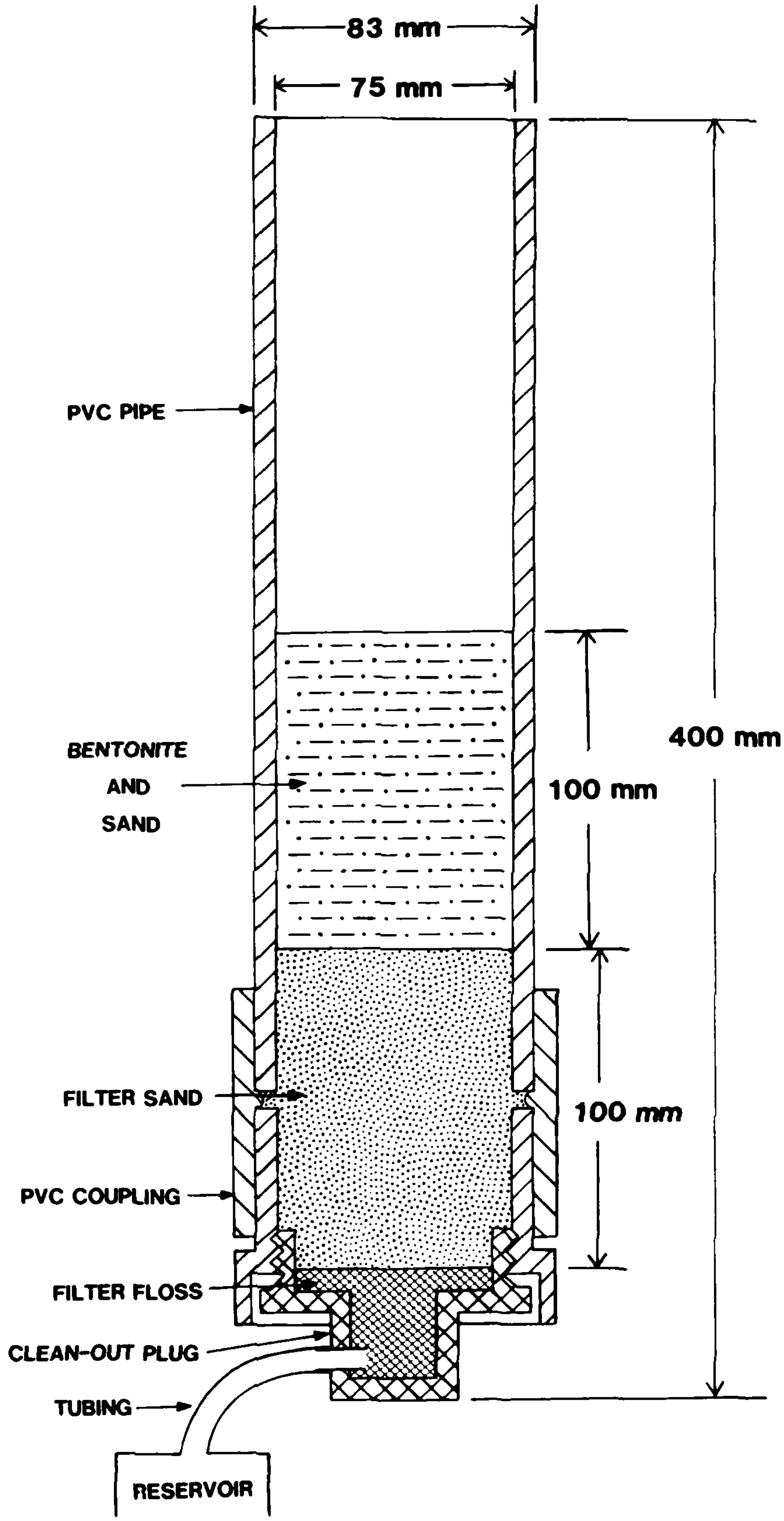

Figure 1. Cross-section of the test cell used in the real-time liner test

48 hours to verify that no water would drain from the test cell in its initial condition. The water above the simulated liner was decanted prior to the addition of the waste.

Simulated waste

13. A saturated acidic lead nitrate solution was prepared by shaking a 10 percent nitric acid solution over excess reagent-grade, crystalline, lead nitrate. The solution was allowed to stand in contact with solid lead nitrate for 48 hours at room temperature. The saturated acidic solution was decanted and used as the permeant.

Preparation and X-raying of test cell

14. The test cell was clamped in a vertical position to a ring stand and the drain tube was connected to the reservoir. The simulated acidic lead nitrate waste was slowly poured into the test cell taking care not to disturb the bentonite/sand liner. The top of the cell was covered with pliable polyethylene film to retard evaporation but was not sealed. The liquid waste was approximate 140 mm (5.5 in.) deep over the simulated liner.

15. Radiographs were taken at one- to five-day intervals until the simulated waste penetrated the liner 16 days after initiation of the test. Additional radiographs were taken at one to two-day intervals until the cell was completely empty, 13 days after initial breakthrough was noted. All radiographs were made using a Norelco MG 300 Industrial X-ray system using a 300 kV tungsten target tube. Kodak Industrex M lead pack film was used. The X-ray unit was operated at 290 kV at 11 mA. Exposure times were varied from 1 to 2 minutes. For publication purposes, prints were prepared from the developed X-ray film. In the prints denser areas in the test cell are dark, not light as they would be in a developed X-ray film.

Mineralogical examination of liner

16. After all X-ray radiographs were completed, samples of the bentonite/sand mixture that had been subjected to the lead nitrate solution were collected from the top layer of the test cell. Samples of the liner material as originally prepared had been collected and stored in sealed containers. The before-testing and after-testing samples were examined using X-ray diffraction. All samples were dried and ground to less than 200-mesh (<74 micro-meters) and examined as packed powder on a General Electric Model 700 Diffractometer using CuK_α radiation. No attempt was made to control the moisture content during analysis.

Soil/Waste Interaction Tests

Preparation of soil

17. Four clay-rich soils of different composition that could be compacted to form pond liners were selected for use in this study. The four clay types represented in the soils were: non-calcareous smectite; calcareous smectite; kaolinite; and illite (mica). Table 1 summarizes the techniques employed in characterizing the soils. The major characteristics and the classification and nomenclature of the test soils are summarized in Table 2.

18. Ten-centimeter (4-inch) diameter compaction permeameter molds as described by Brown and Anderson (1983) were used for hydraulic conductivity (permeability) measurements (Figure 2). All soils were mixed, brought to optimum water content, and equilibrated overnight prior to compaction. Compaction was done in three equal lifts using 25 blows per lift of a 2.41 kg (5.5 lb) hammer falling 30 cm (12 in.) on a mechanical compactor (Soil Test Model CN 4230, ASTM Procedures 1557; 698). Lifts consisted of 600, 650, 750, and 750 g for the calcareous smectite, noncalcareous smectite, mica, and kaolinite soils, respectively. The compacted samples were 11.6 cm (4.58 in.) in height. The procedures are the same ones used by Brown and Anderson (1983). After compaction, the appropriate permeant was applied to the soil surface and allowed to stand at atmospheric pressure overnight.

Preparation of permeants

19. Five fluids were prepared as experimental permeants (Table 3). A calcium sulfate solution provided a permeability baseline. Acetate and nitrate solutions represented typical acidic wastes. Acetone and xylene were selected because they represent common organic solvents used in painting, printing and metal cleaning operations and would typically be found in waste suspensions. The lead paint pigment was added to provide a radio-opaque tracer that permitted the movement of the suspended solid material to be observed in radiographs. The lead paint pigment used was lead tetroxide, red lead (Pb_3O_4) obtained from lead primer paint.

Test procedures

20. Three replicate samples were tested for each permeant/soil pair for a total of 60 tests. The permeameters were pressurized with clean, compressed air to 207 kPa (30 psi). The increased head was used so the permeability measurements could be completed within a reasonable time.

Table 1

Techniques Employed in Characterizing Soil Samples

Characteristic	Technique	Reference
Texture	Visual	Day, 1965
Cation Exchange Capacity	Wet Analysis	Chapman, 1965
pH and Alkalinity	Electrometric titration	Peech, 1965
Atterberg Limits	--	Sowers, 1965
Mineralogy	X-ray diffraction	Whittig, 1965

Table 2

Physical and Chemical Characteristics of the Four Soils Studied

	USDA Soil Series			
Characteristic	Lufkin	Houston Black	Elgin	Ranger Yellow
Major clay mineral present	non-calcareous smectite	calcareous smectite	kaolinite	illite (mica)
Sand (wt %)*	36	6.8	62.8	60.4
Silt (wt %)	27	47.1	13.6	17.6
Clay (wt %)	37	46.1	24.5	22.0
Liquid limit	54.4	50.6	20.5	21.6
Plastic limit	28.1	40.0	14.3	14.1
Dry Density (g/cm^3)	1.44	1.34	1.90	1.98
Cation Exchange Capacity (meq/100g)	24.2	36.8	14.1	14.9
Alkalinity (ppm)	3.3	129.2	--	--
pH	6.1	7.9	7.7	8.0
Mineralogy	QZ-1**	M-1	--	MI-1
	K-2	K-2	K-1	K-2
	M-2	QZ-3	M-tr	M-3
Source	Brazos Co., Texas	Bell Co., Texas	Bastrop Co., Texas	Eastland Co., Texas
Nomenclature	*Vertic Albaqualfs*	*Udic Pellusterts*	--	--

* Size classification follows Day (1965).

** QZ = quartz; K - kaolinite; MI = mica; M = montmorillonite.
1 = >40%; 2 = 10-40%; 3 = <10%; tr = trace.

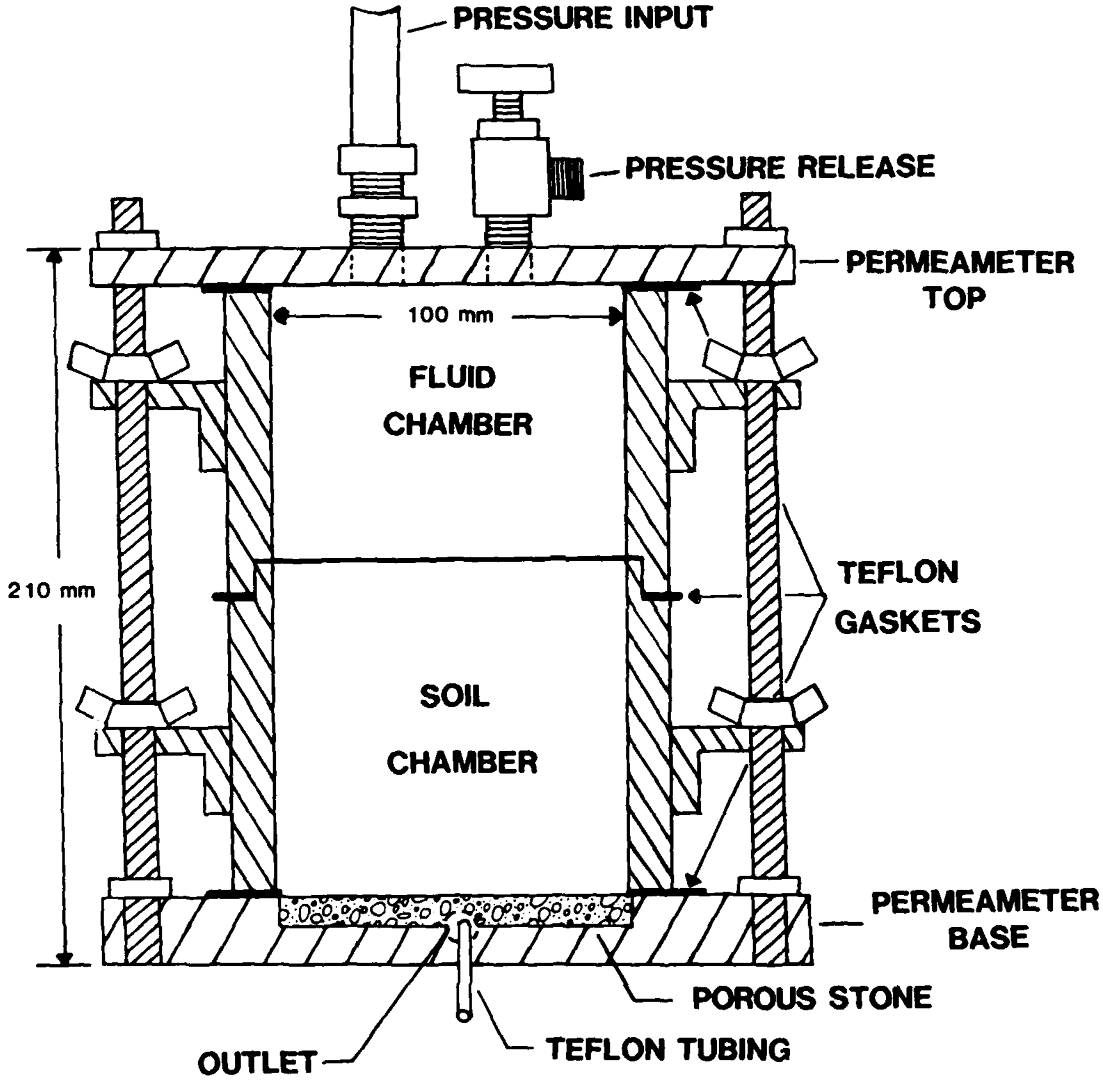

Figure 2. Cross-section of permeameter used in the study of soil/waste interaction

Table 3

Experimental Permeants for Soil/Waste Testing

Test Liquid	Composition
Water (0.01 N $CaSO_4$)	0.068% $CaSO_4$
Lead acetate solution (saturated)	~60% Pb $(C_2H_3O_2)_2$*
Lead nitrate in 0.1% HNO_3 (saturated)	~50% Pb $(NO_3)_2$*
Acetone containing lead tetroxide	Pb_3O_4 suspension**
Xylene containing lead tetroxide	Pb_3O_4 suspension**

* Reacts slowly with CO_2 to produce $PbCO_3$ that is insoluble.

** Approximately 200 to 250 ml of settled paint pigment was added to each 600 ml aliquot of xylene or acetate used for testing.

After sealing, the cells were not opened until the permeation testing was completed. Leachate was collected daily or more frequently depending on the hydraulic conductivity, and the leachate volume was measured. Hydraulic conductivity was calculated using Darcy's Law in the following form:

$$K = \frac{vl}{A\ t\ \Delta h}$$

where

K = hydraulic conductivity, cm/sec

v = volume of liquid passed through the core, cm^3

l = length of the soil core, cm

A = cross-sectional area of the soil core, cm^2

t = time, sec

Δh = difference in hydraulic head between the top and bottom of the soil core, cm of water

21. The hydraulic conductivities obtained with Darcy's law can be normalized for liquids with various viscosities and densities by multiplying by the density and dividing by the viscosity of the permeant. In this report the changes in hydraulic conductivity in a single soil type over the course of a permeability test was the information of interest; therefore the normalization of the data was not needed. The volume discharged from each column was

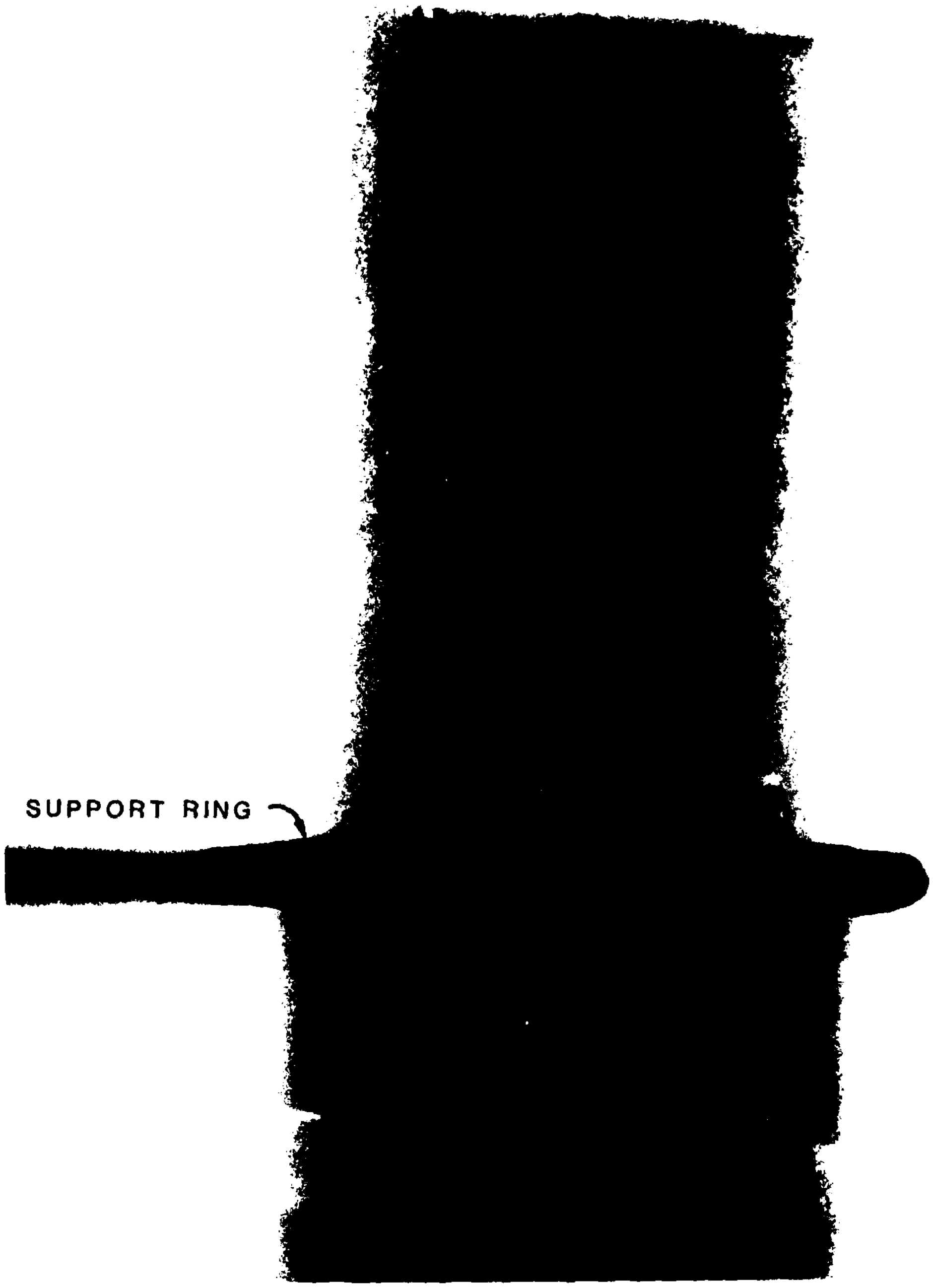

Figure 3. Print of radiograph of simulated liner before application of acidic $Pb(NO_3)_2$ solution

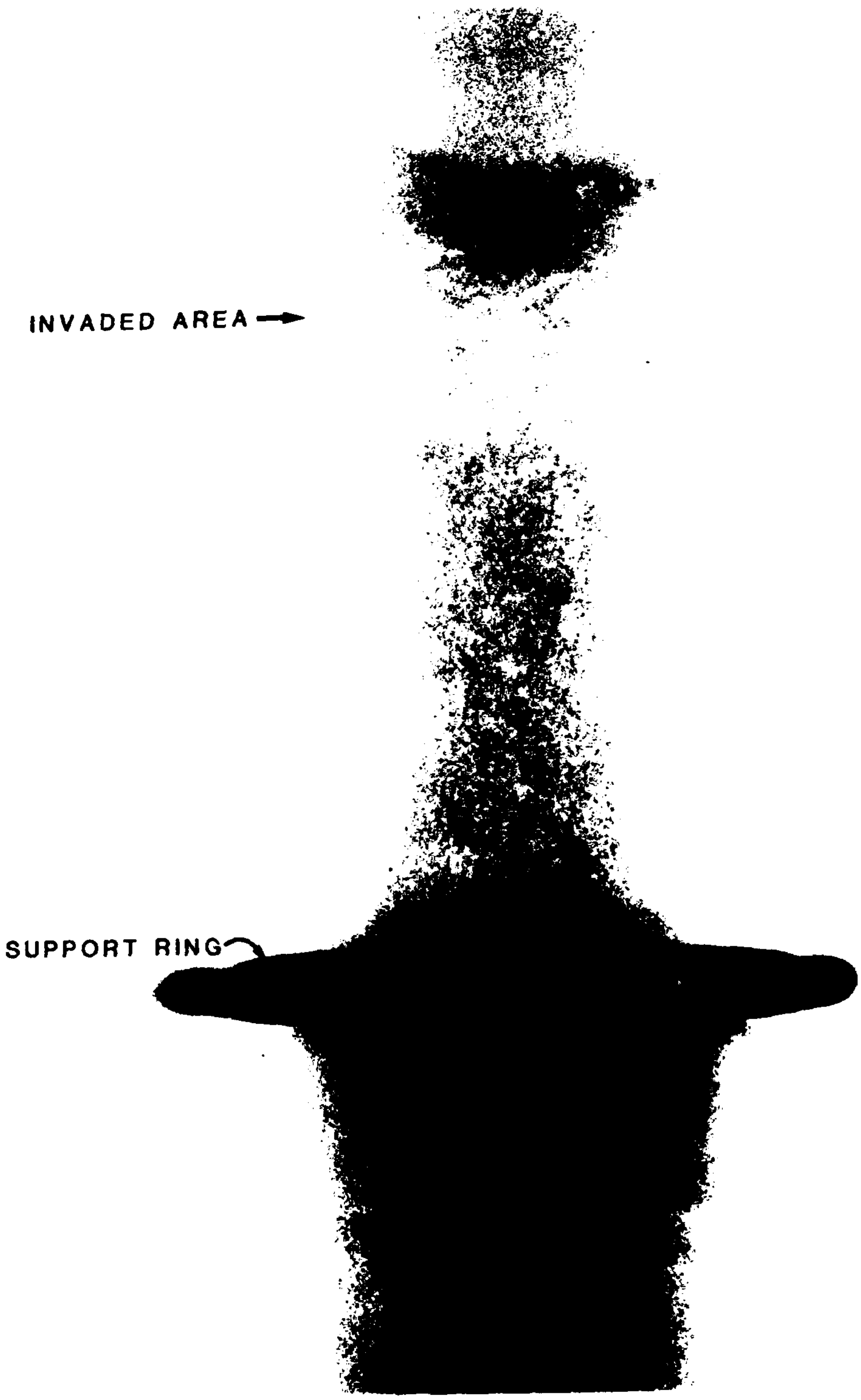

Figure 4. Print of radiograph of simulated liner one day after application of acidic $Pb(NO_3)_2$ solution

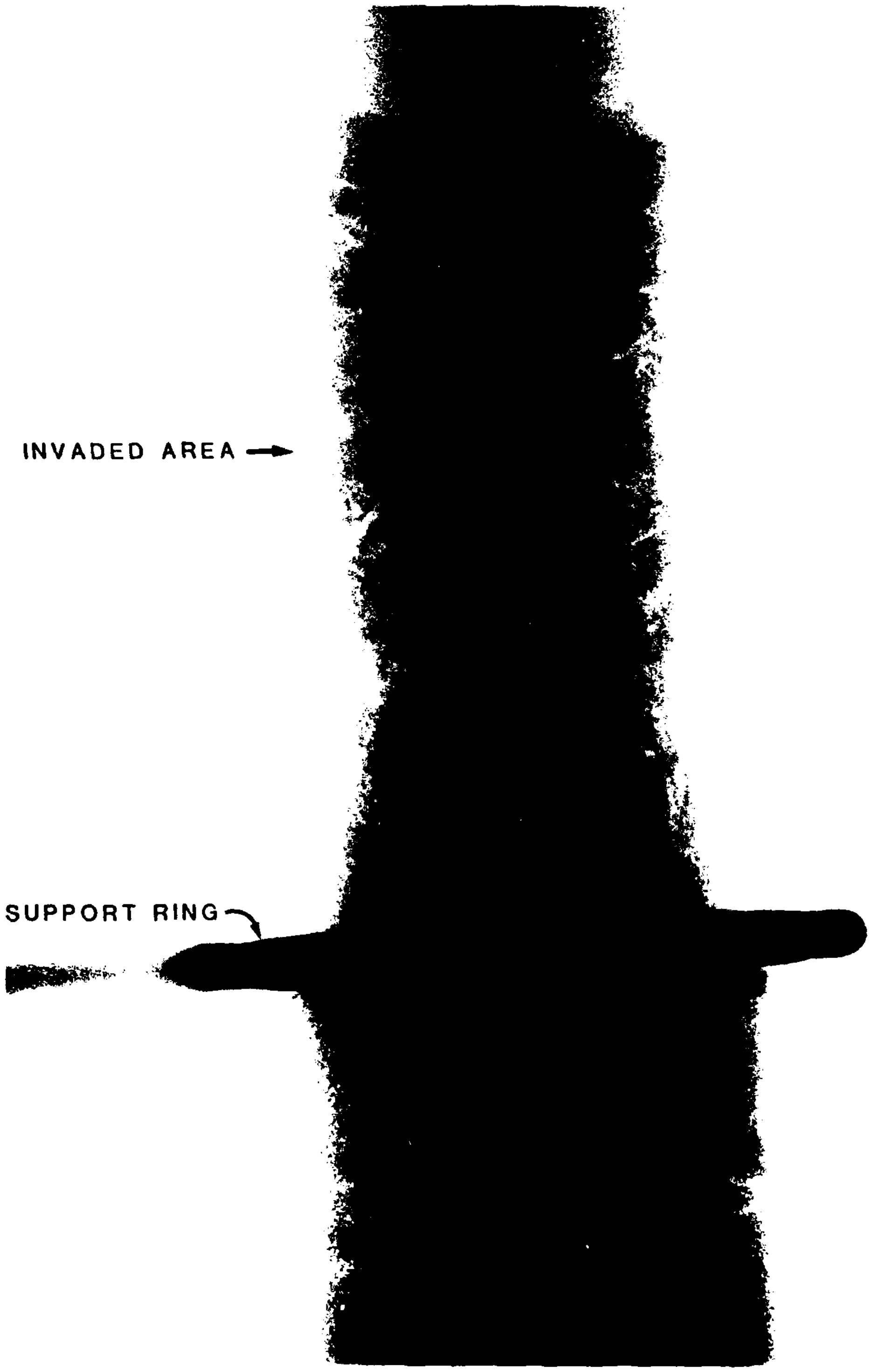

Figure 5. Print of radiograph of simulated liner 25 days after application of acidic $Pb(NO_3)_2$ solution

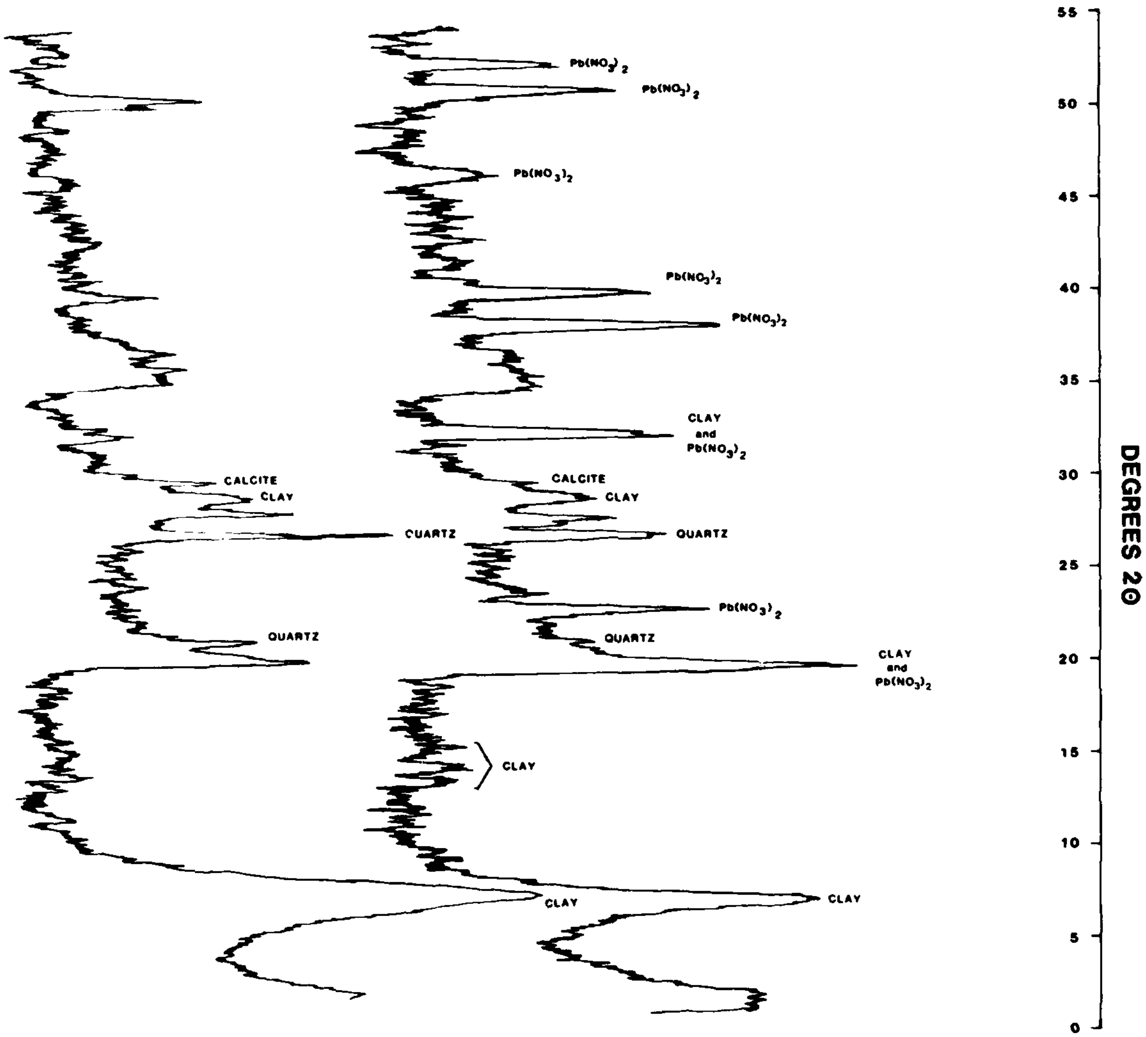

Figure 6. Comparison of X-ray diffraction traces produced from simulated clay liner before (left trace) and after (right trace) application of acidic $Pb(NO_3)_2$ solution

materials (such as lead compounds) removes a requirement to make the test permeant different from the actual waste and also eliminates the problem of handling potentially toxic salts (like lead nitrate).

Applications of real-time examination

28. X-ray examination made during permeability testing of liner materials (such as the bentonite/sand mix used here) can provide immediate information on the quality of sample preparation (sample homogeneity and sample packing) and on test equipment performance (leaks and side wall effects). The development of a pattern of fluid movement and changes in liner appearance are helpful in interpreting the mechanisms involved in a liner failure. Where structural changes in liners are being investigated, a radio-opaque tracer is not needed. If fluid movement is a major concern, it should be possible to select stable radio-opaque compounds or radio-opaque organometalic complexes that can be used as tracers.

Soil/Waste Interaction Test Results

29. The results of the permeability tests of the compacted soils with the experimental permeants are summarized in Appendix A. The data on swelling of the soils measured after permeation are presented in Table 4.

Non-calcareous smectite

30. The non-calcareous smectite showed low permeabilities when subjected to the 0.01 N $CaSO_4$ solution. In two replicates (identified as REP 1 and REP 2) the permeability started at 1×10^{-6} cm/sec and dropped and the third sample (REP 3) showed a very low initial permeability (Figure 7). The decreased permeability with continued flow could be related to the swelling observed in these samples (Table 4). In tests using lead acetate as the permeant a similar low permeability was noted (Figure 8). The radiographs of the samples indicate that lead was interacting with and precipitating in the compacted soil. Figure 9 shows that the non-calcareous smectite developed a precipitate with a fiberous texture, suggesting that lead compounds were precipitating or being absorbed into the liner. Permeability was decreased, but the liner was partly penetrated and had reacted with the permeant. The acidic lead nitrate solution (Figure 10) produced a large increase in permeability (from initial conductivity of 10^{-8} cm/sec to 10^{-6} cm sec). The X-ray examination of the samples showed irregular connecting voids suggesting the clay

Table 4

Soil Swelling in Cores After Permeation with Various Liquids

Permeant	Replicate Number	Non-calcareous Spectite, % Swelling*	Calcareous Smectite, % Swelling	Kaolinite % Swelling	Illite % Swelling
0.01 N $CaSO_4$	1	0.8	0	0.9	0
	2	1.5	1.2	0	0.7
	3	0	1.0	0	0
Lead Acetate	1	2.7	2.3	0.6	1.5
	2	2.6	2.2	2.0	1.5
	3	0	2.5	0	1.3
Acetone with lead paint pigment	1	0	0	0	0
	2	0	0	0	0
	3	0	0	0	0
Xylene with lead paint pigment	1	0	0	0	0
	2	0	0	0	0
	3	0	0	0	0
0.1% HNO_3 with Pb $(NO_3)_2$	1	1.6	2.7	0	0
	2	1.0	2.9	0	0
	3	0.6	2.6	0	2.5

* % swelling is the change in height divided by the original height and multiplied by 100.

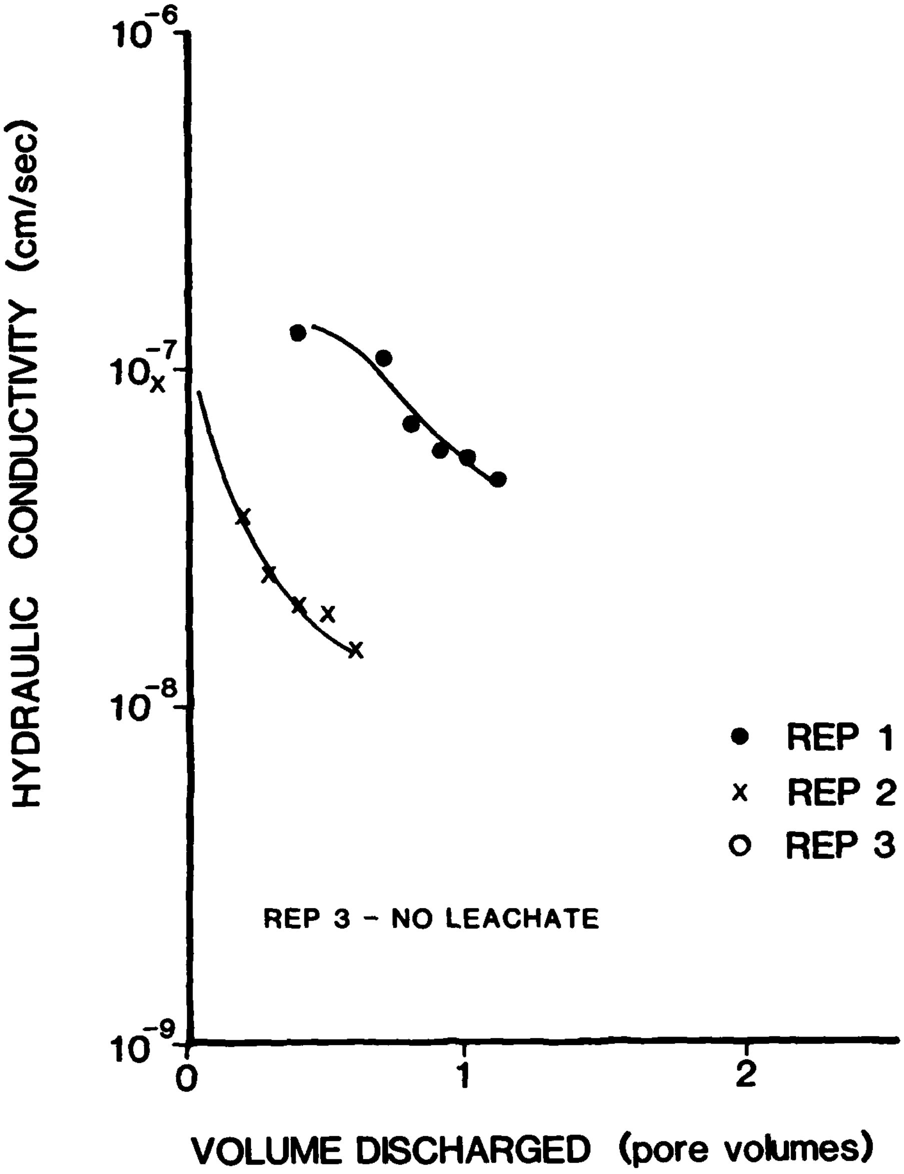

Figure 7. Hydraulic conductivity of unsaturated non-calcareous smectite measured using 0.01 N $CaSO_4$

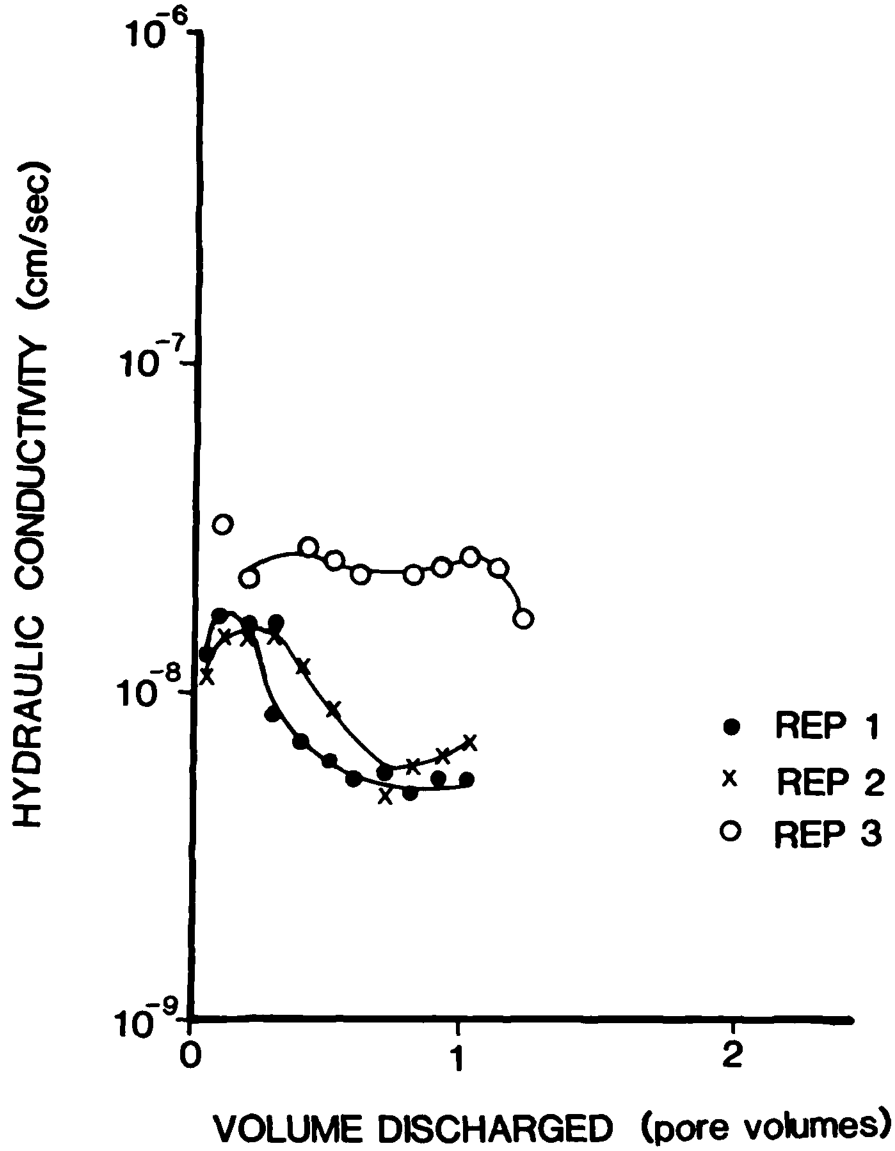

Figure 8. Hydraulic conductivity of unsaturated non-calcareous smectite measured using saturated lead acetate solution

Figure 9. Print of radiograph of non-calcareous smectite soil permeated with lead acetate solution, whole sample, actual size (Replicate 3)

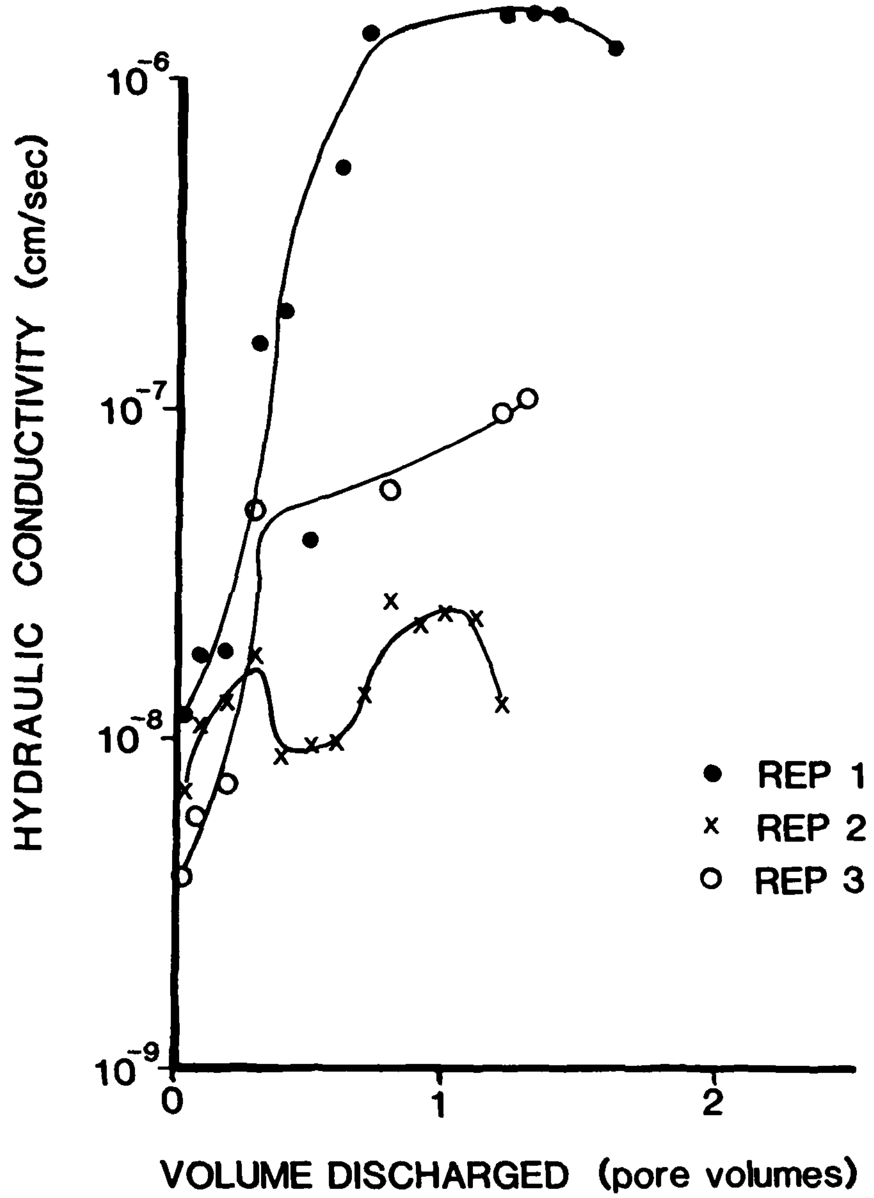

Figure 10. Hydraulic conductivity of unsaturated non-calcareous smectite measured using 0.1% HNO_3 saturated with Pb $(NO_3)_2$

had developed a flocculated (or blocky) structure (Figure 11) similar to the structure that had occurred with the bentonite/sand mixture (which also contained smectite) in the real-time liner failure study (Figure 5). Exposure of the non-calcareous smectite to acetone or xylene suspensions of paint pigment produced very low permeabilities (Figure 12). The radiographs of these samples showed the paint pigments produced a plugging on the soil surface and only minor penetration of the samples occurred (Figure 13).

Calcareous smectite

31. The calcareous smectite showed a typical low (1×10^{-6} cm/sec) and decreasing permeability when tested with 0.01 N $CaSO_4$ (Figure 14). The appearance of three "lifts" of soil packed during preparation of the samples can be noted in Figure 15 but the samples are relatively featureless. Permeation with lead acetate produced a pronounced reduction in permeability (Figure 16). Radiographs prepared from the lead acetate permeated samples show an irregular darkened pattern indicating precipitation of lead in the sample (Figure 17) and indicate that permeation was not uniform across the entire diameter of the sample. Samples of the calcareous smectite showed an increase in hydraulic conductivity when attacked with the acidic lead nitrate (Figure 18), but the increase was less than that observed in the non-calcareous smectite. Radiographs of the calcareous smectite show a dark pattern indicating lead was deposited in the soil but there is no pronounced change in soil structure (Figure 19), as was observed in the non-calcareous smectite. The samples permeated with paint pigments suspended in acetone showed variable hydraulic conductivities suggesting side wall leakage (Figure 20), but this could not be confirmed from the radiographs. The suspected samples looked similar to plugged samples. If the liquid separates from the suspended lead compounds, liquid movement cannot be traced. Exposure of the samples to suspended paint pigments in xylene resulted in reduced hydraulic conductivities (Figure 21). Radiographs indicated the suspended paint solid plugged the tops of the samples (Figure 22).

Kaolinite

32. The kaolinitic soil showed low hydraulic conductivities (1×10^{-7} cm/sec) when 0.01 N $CaSO_4$ was used as a permeant (Figure 23). Lead acetate solution produced no increase in hydraulic conductivity (Figure 24) although the X-ray indicates that lead acetate had invaded the outer section of the permeameter sample (Figure 25). The uneven pattern of lead

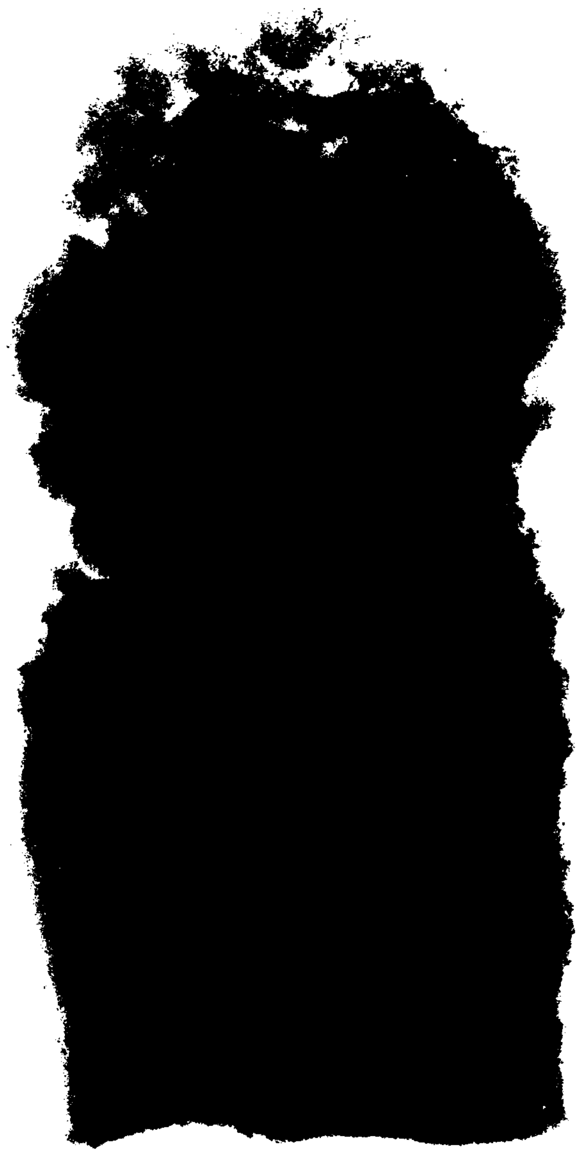

Figure 11. Print of radiograph of non-calcareous smectite soil permeated with acidic lead nitrate solution, whole sample, actual size (Replicate 1)

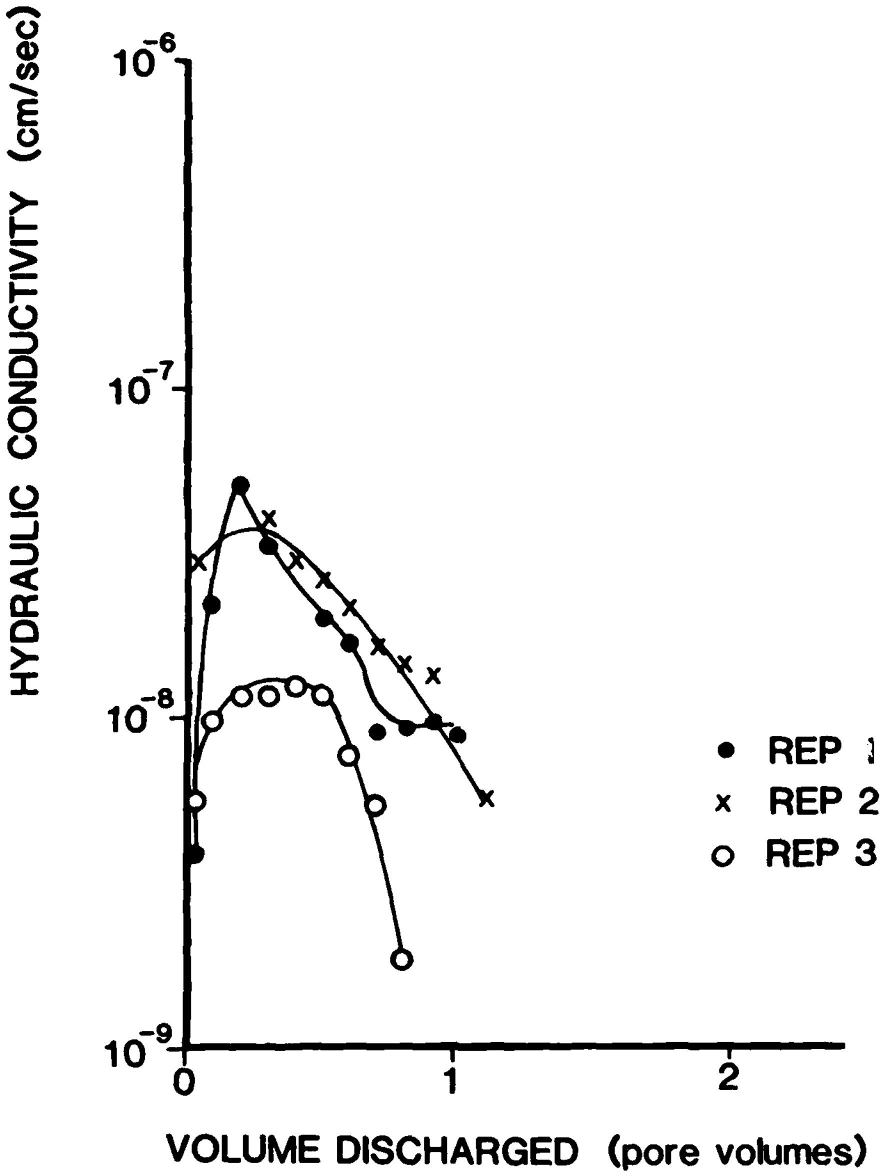

Figure 12. Hydraulic conductivity of unsaturated non-calcareous smectite measured using xylene containing lead paint pigment

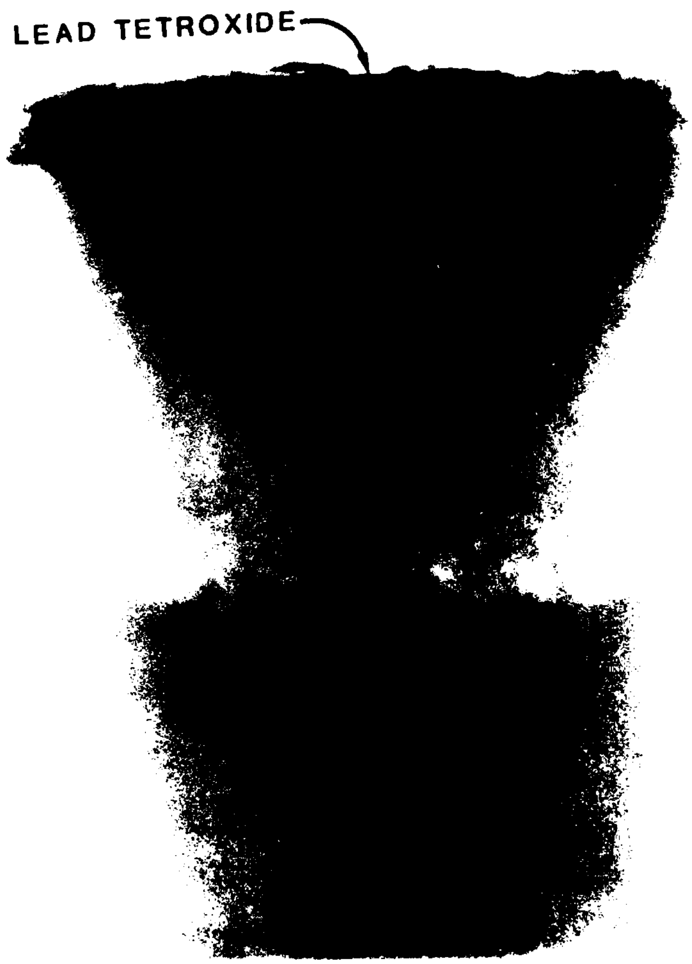

Figure 13. Print of radiograph of non-calcareous smectite soil tested with lead paint pigment/xylene suspension, whole sample, actual size (Replicate 1)

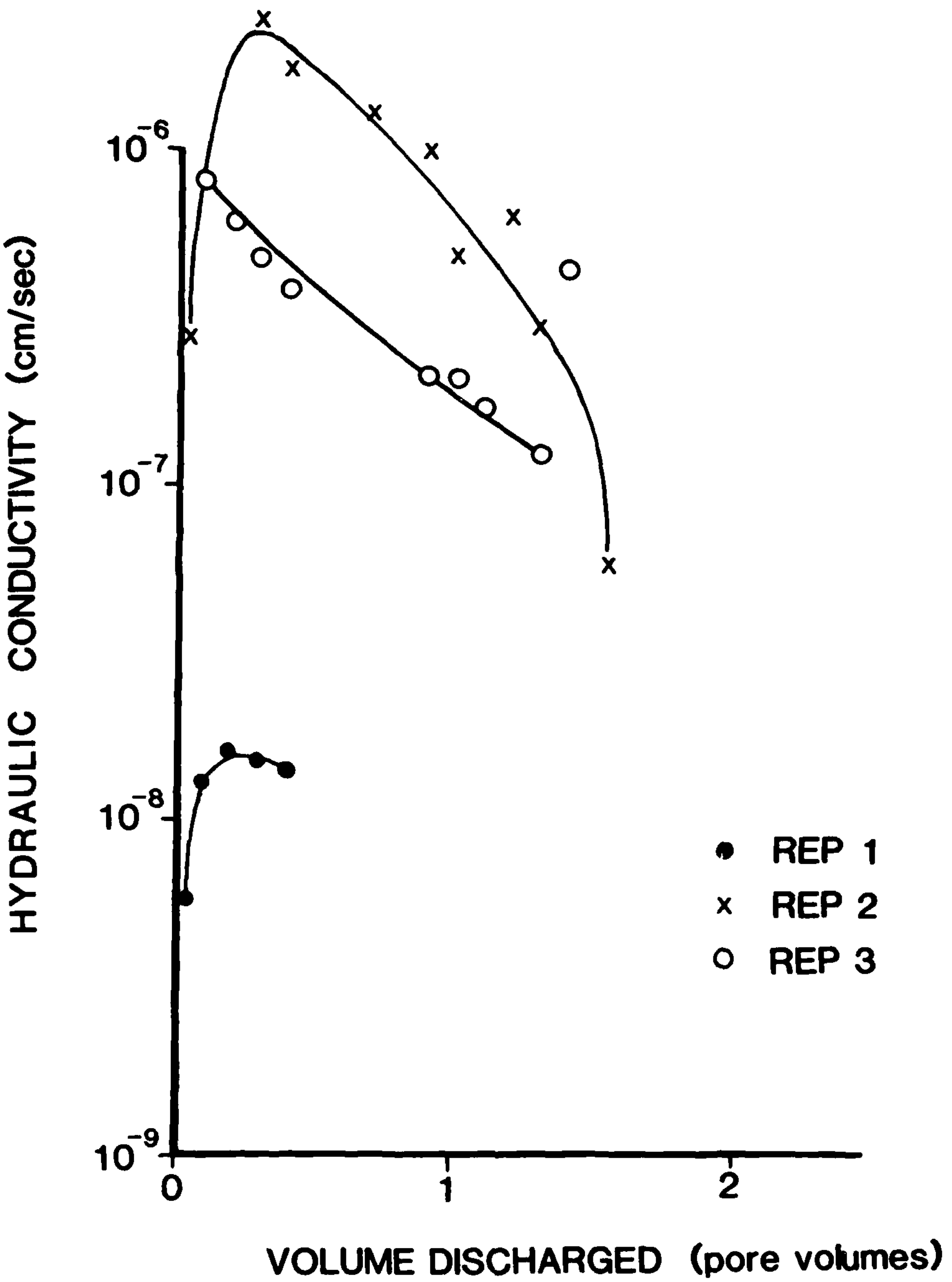

Figure 14. Hydraulic conductivity of unsaturated calcareous smectite measured using 0.01 N $CaSO_4$

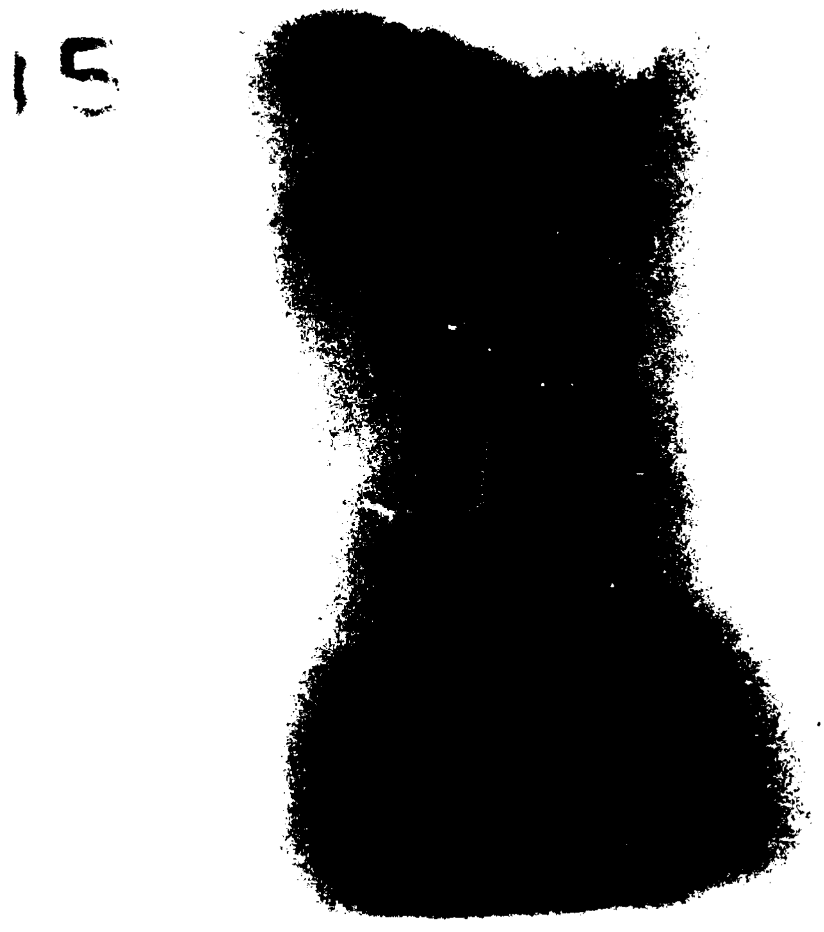

Figure 15. Print of radiograph of calcareous smectitic soil permeated with 0.01 N $CaSO_4$, whole sample, actual size (Replicate 1)

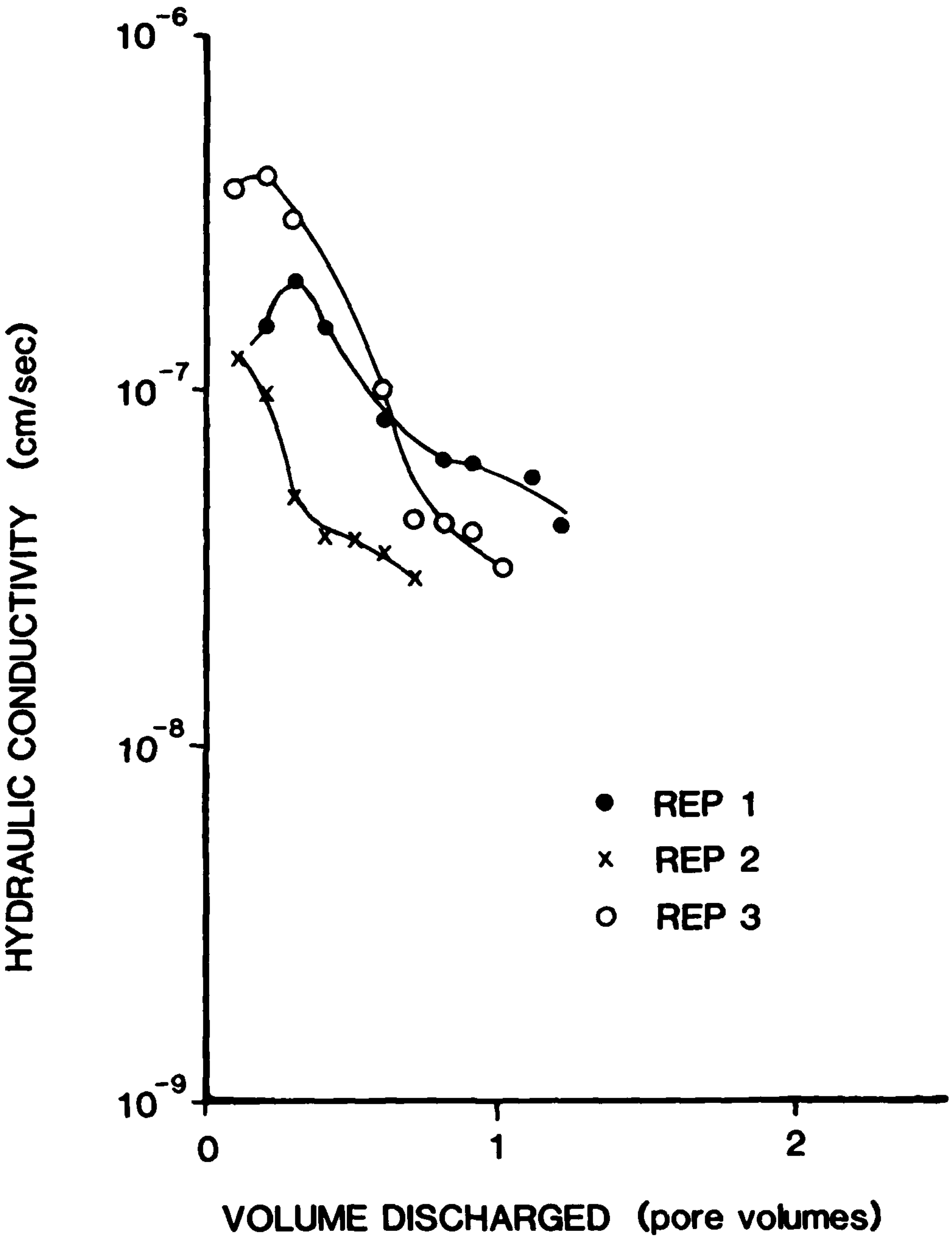

Figure 16. Hydraulic conductivity of unsaturated calcareous smectite measured using saturated lead acetate solution

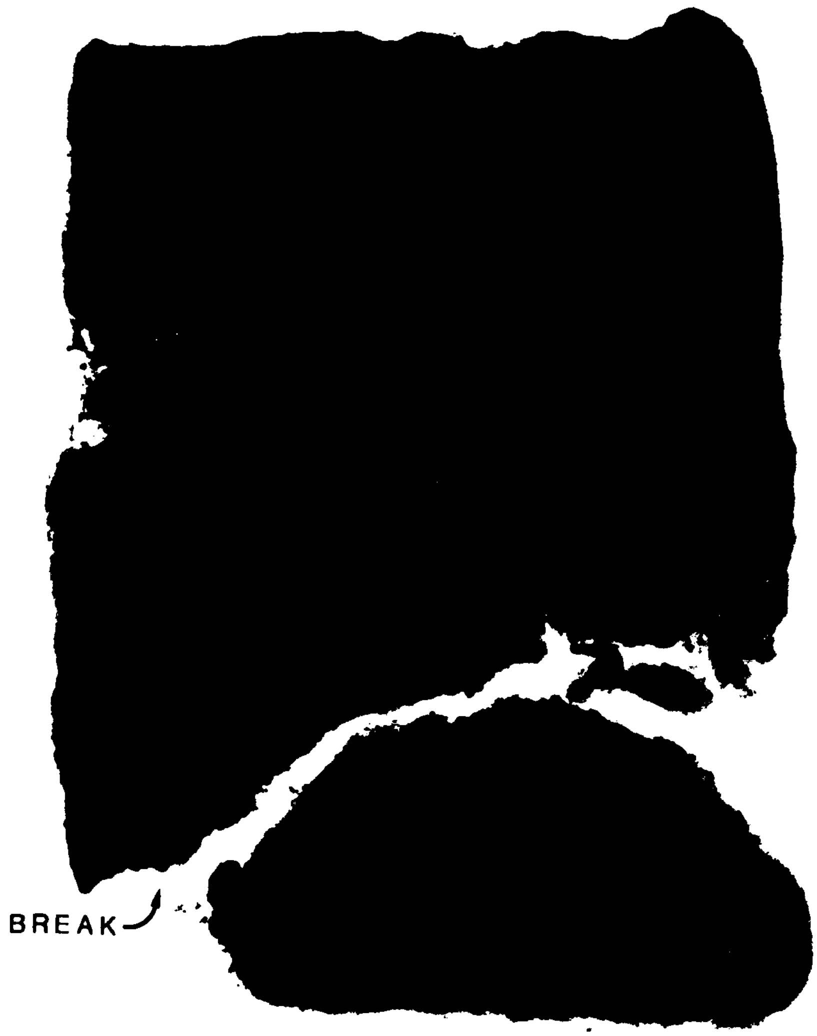

Figure 17. Print of radiograph of calcareous smectitic soil permeated with lead acetate solution, sectioned sample, actual size (Replicate 2)

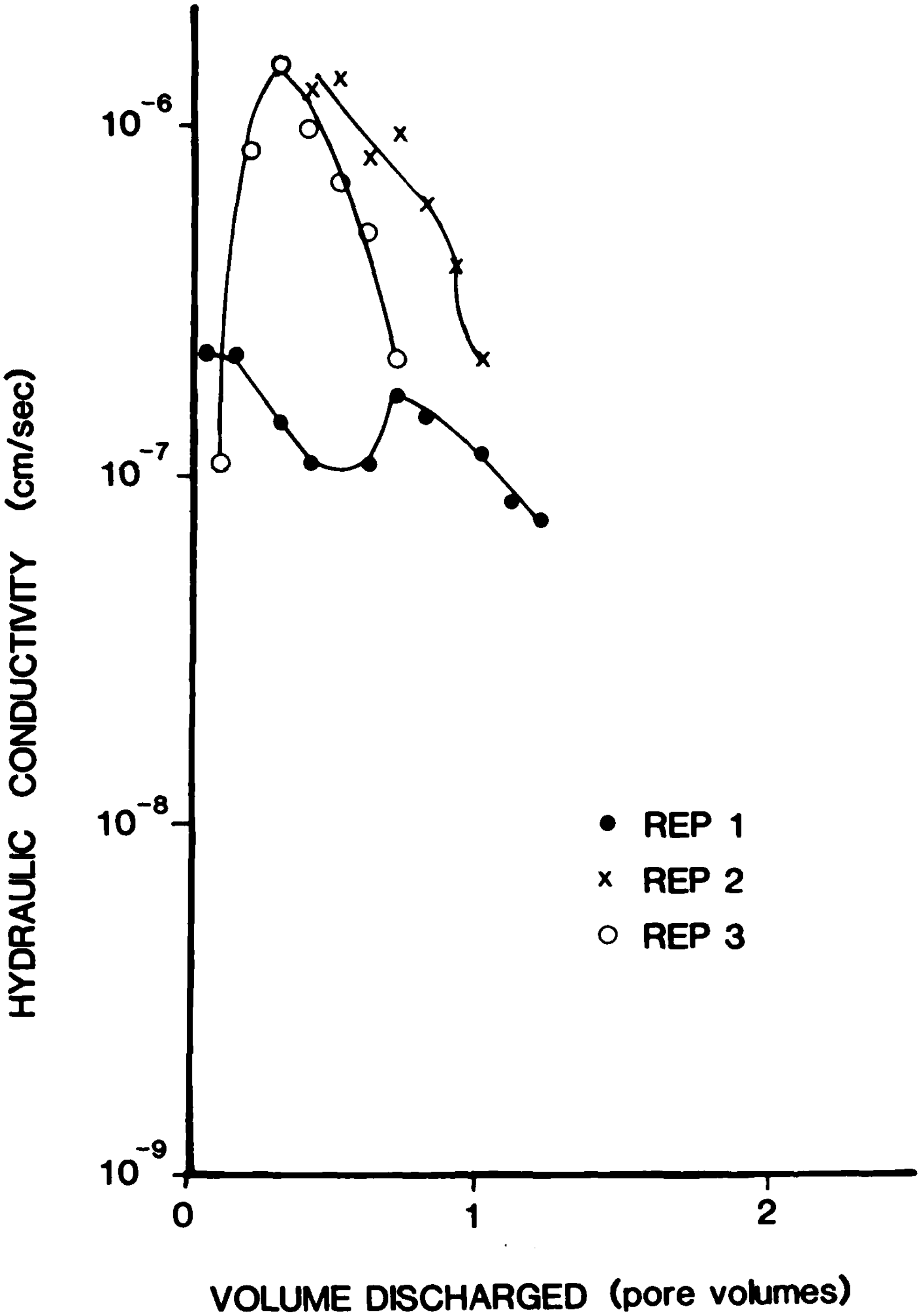

Figure 18. Hydraulic conductivity of unsaturated calcareous smectite measured using 0.1% HNO_3 saturated with $Pb(NO_3)_2$

Figure 19. Print of radiograph of calcareous smectitic soil permeated with acidic lead nitrate solution, sectioned sample, actual size (Replicate 3)

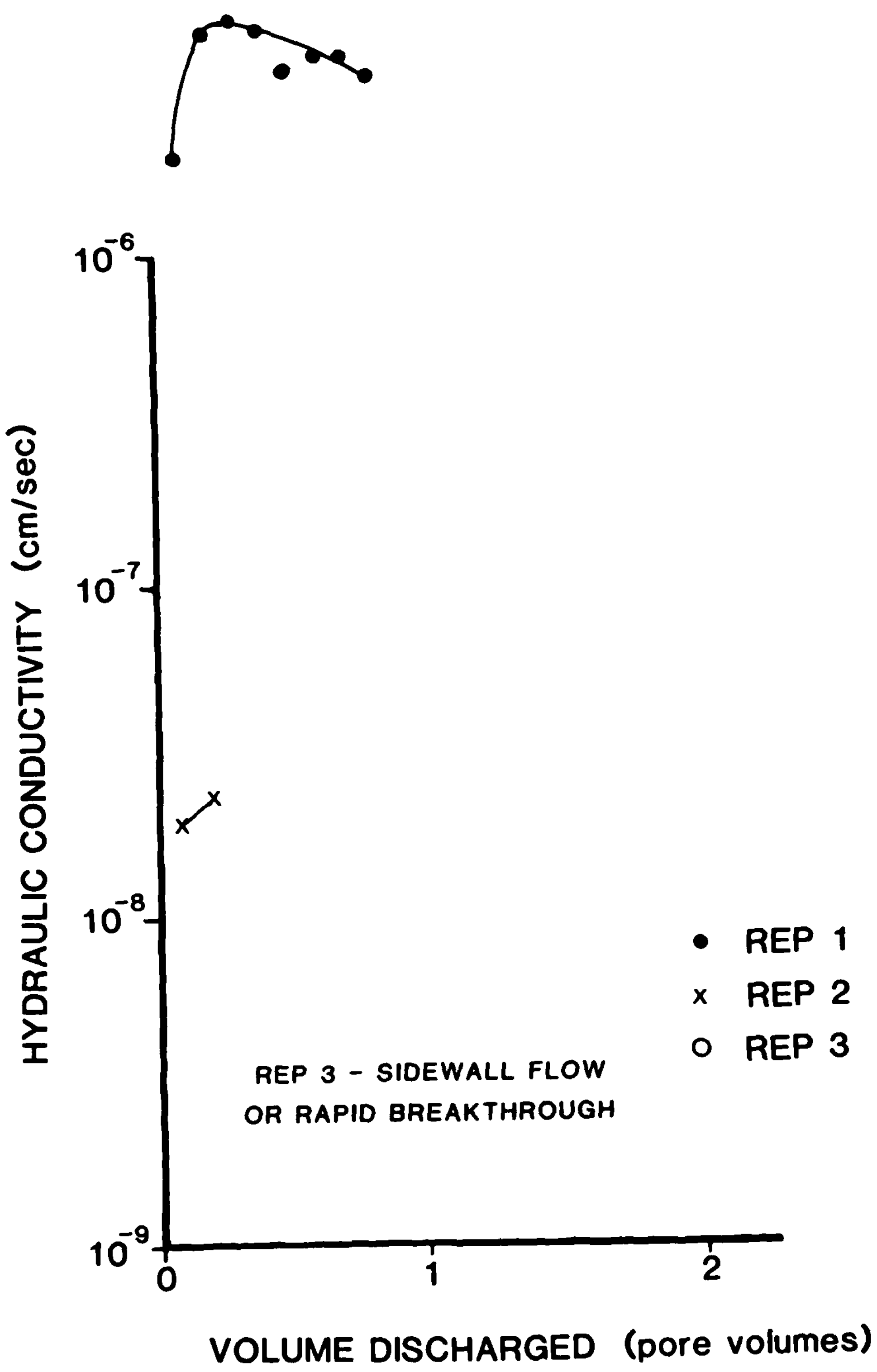

Figure 20. Hydraulic conductivity of unsaturated calcareous smectite measured using acetone containing lead paint pigment

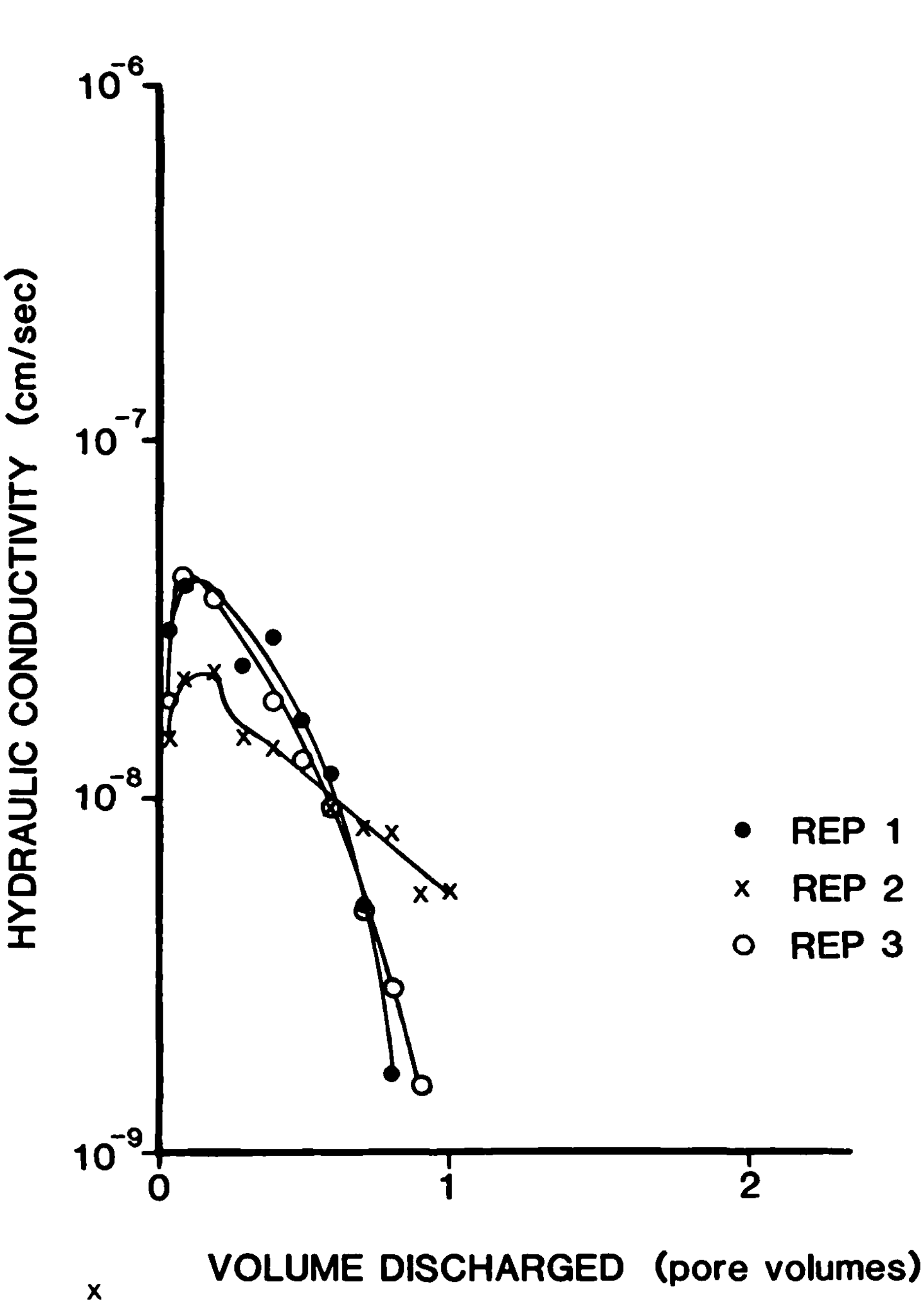

Figure 21. Hydraulic conductivity of unsaturated calcareous smectite measured using xylene containing lead paint pigment

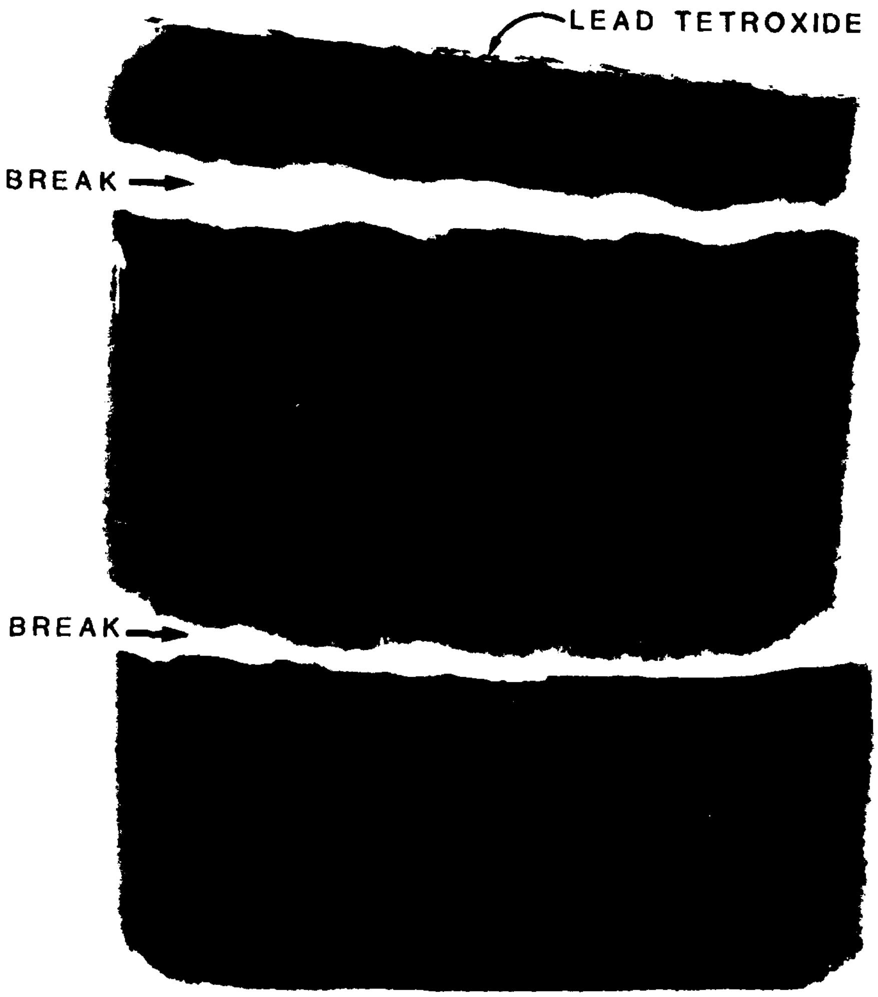

Figure 22. Print of radiograph of calcareous smectitic soil tested with lead paint pigment/xylene suspension, sectioned sample, actual size (Replicate 1)

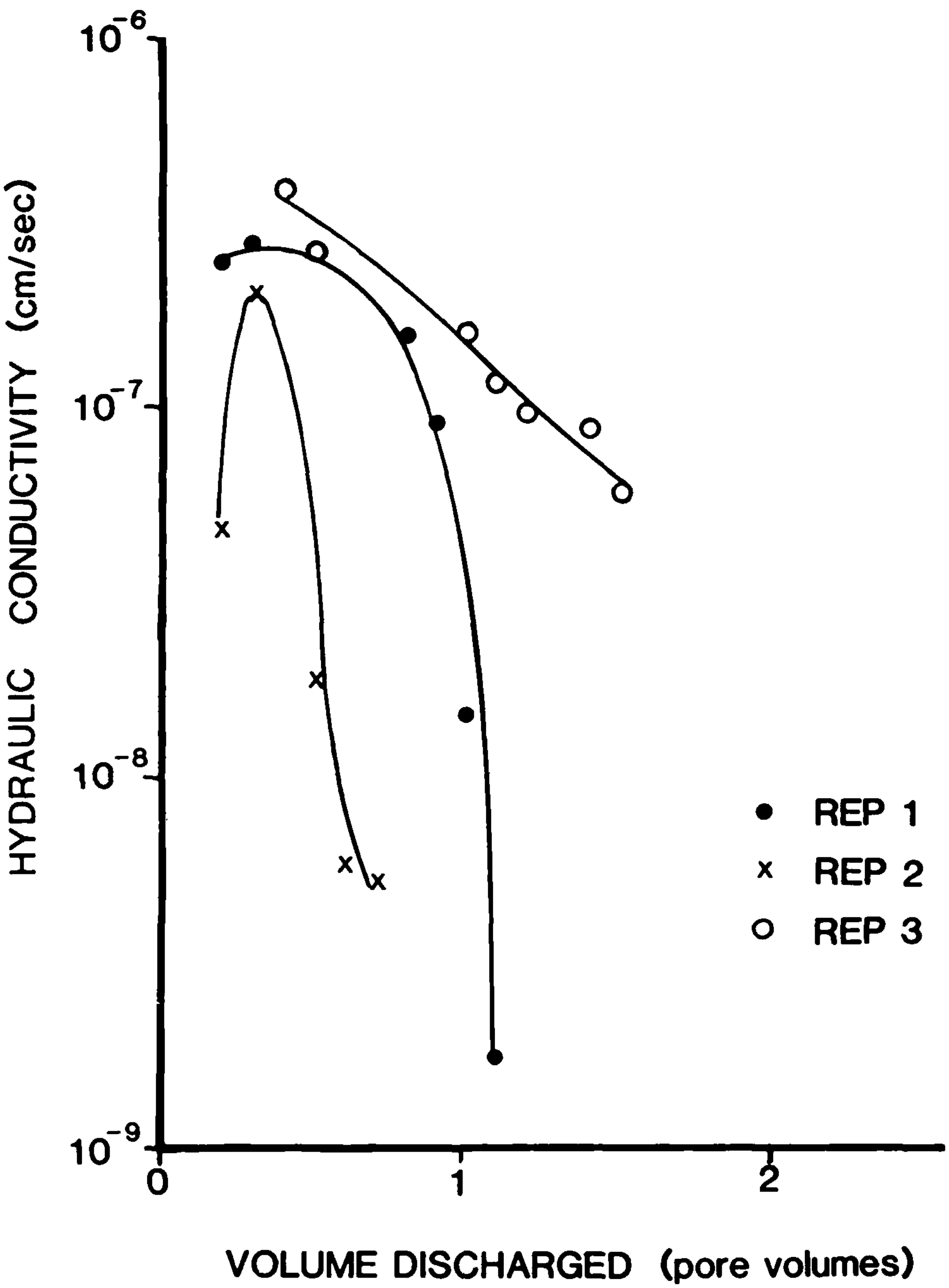

Figure 23. Hydraulic conductivity of unsaturated kaolinitic soil measured using 0.01 N $CaSO_4$

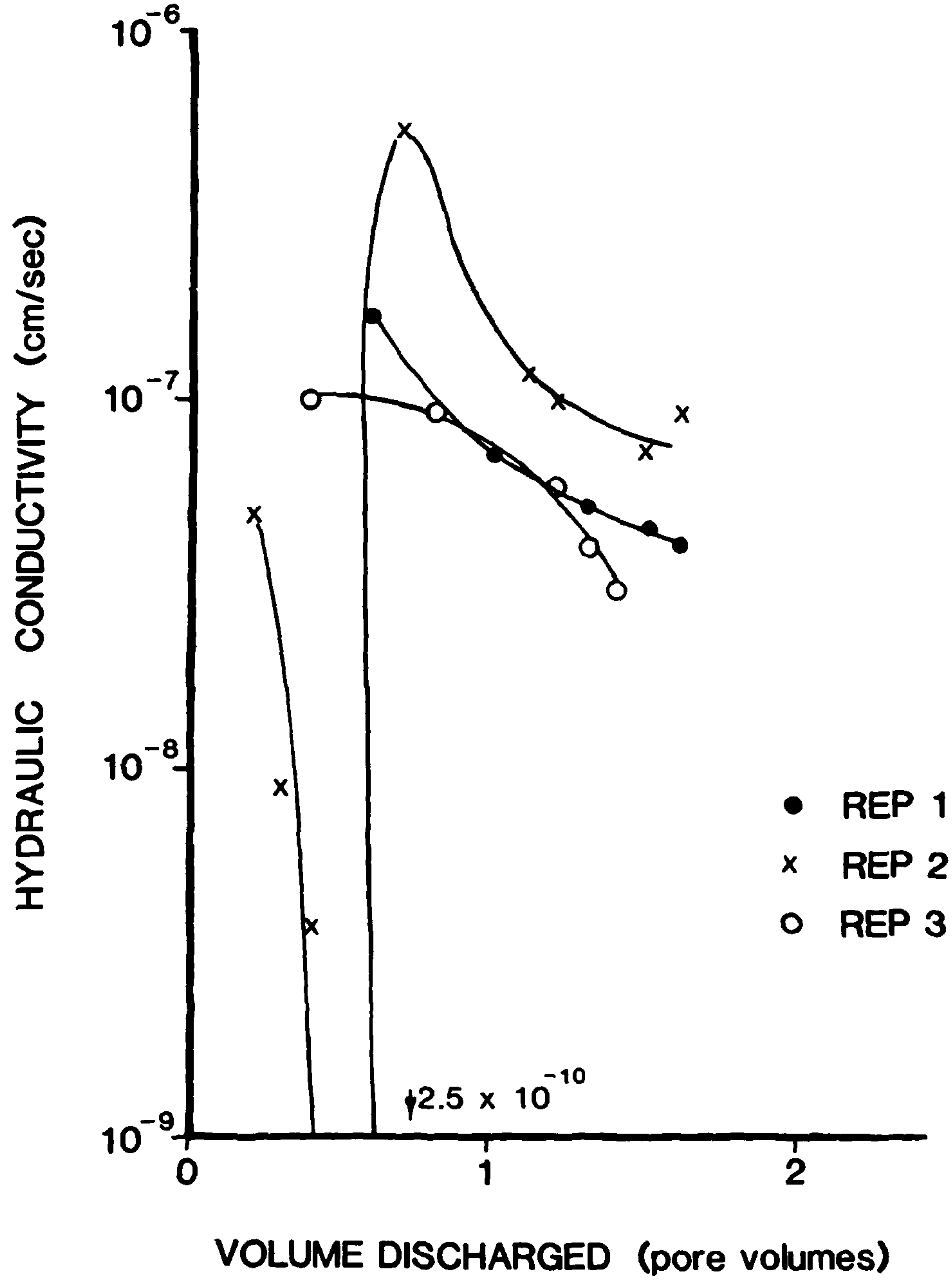

Figure 24. Hydraulic conductivity of unsaturated kaolinitic soil measured using a saturated lead acetate solution

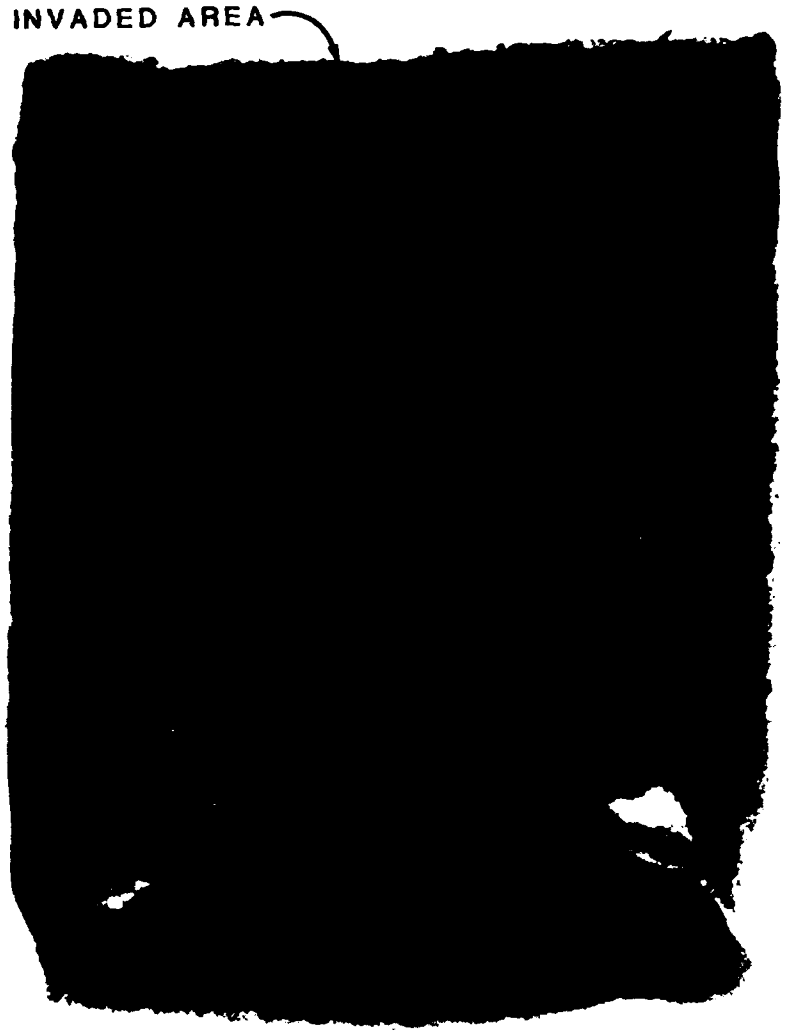

Figure 25. Print of radiograph of kaolinitic soil permeated with lead acetate solution, sectioned sample, actual size (Replicate 1)

precipitation in the radiograph indicates initial leakage along the side walls with precipitation of lead compounds producing a tighter seal. Exposure to the acidic lead nitrate solution increased the conductivity to 1×10^{-6} cm/sec and above (Figure 26). The radiographs of the soil (Figure 27) showed uneven invasion of the lead nitrate with flow along the side walls and extensive precipitation of lead along the bottom of the permeameter sample. Both suspended lead paint pigments produced clogging in the samples and the permeabilities dropped into the range 1×10^{-8} to 2×10^{-9} cm sec (Figures 28 and 29).

Illite

33. The illitic or micaceous soil had a hydraulic conductivity of 1×10^{-8} cm/sec when 0.01 $CaSO_4$ was used as a permeant (Figure 30). The lead acetate solution produced similar hydraulic conductivities (Figure 31), but the radiographs prepared from the lead acetate-permeated samples show that the lead solution had precipitated in the upper parts of the soil samples (Figure 32). Although the hydraulic conductivity did not change, the soil showed strong interaction with the permeant. The exposure to the acidic lead nitrate increased the hydraulic conductivity initially with the hydraulic conductivity later decreasing (Figure 33). The radiographs prepared from the soil sample showed that permeation of the nitric acid was uneven with most extensive invasion in the center of the sample with uninvaded areas along the side walls (Figure 34). The lead precipitating in the soil may have produced clogging. The suspended paint pigments produced a slight increase in conductivity but the paint pigments clogged the soil surface to reduce any change in conductivity (Figures 35 and 36).

Application of post-testing examination

34. The X-ray examination of the samples after permeation was helpful in understanding the results obtained from hydraulic conductivity testing and for showing the changes in the soil structure that indicate a liner failure will occur. For example, Figure 10 shows that lead nitrate produced a 100-fold increase in hydraulic conductivity in the non-calcareous smectite (replicate 1) and the radiograph confirms that the structure of the clay is thoroughly altered. Replicates 2 and 3 showed smaller increases in hydraulic conductivity but the alteration at the top of these samples is similar to changes observed in replicate 1 (Figure 11). The X-ray examination suggested replicates 2 and 3 could be easily altered to become as permeable as replicate 1, if testing had continued.

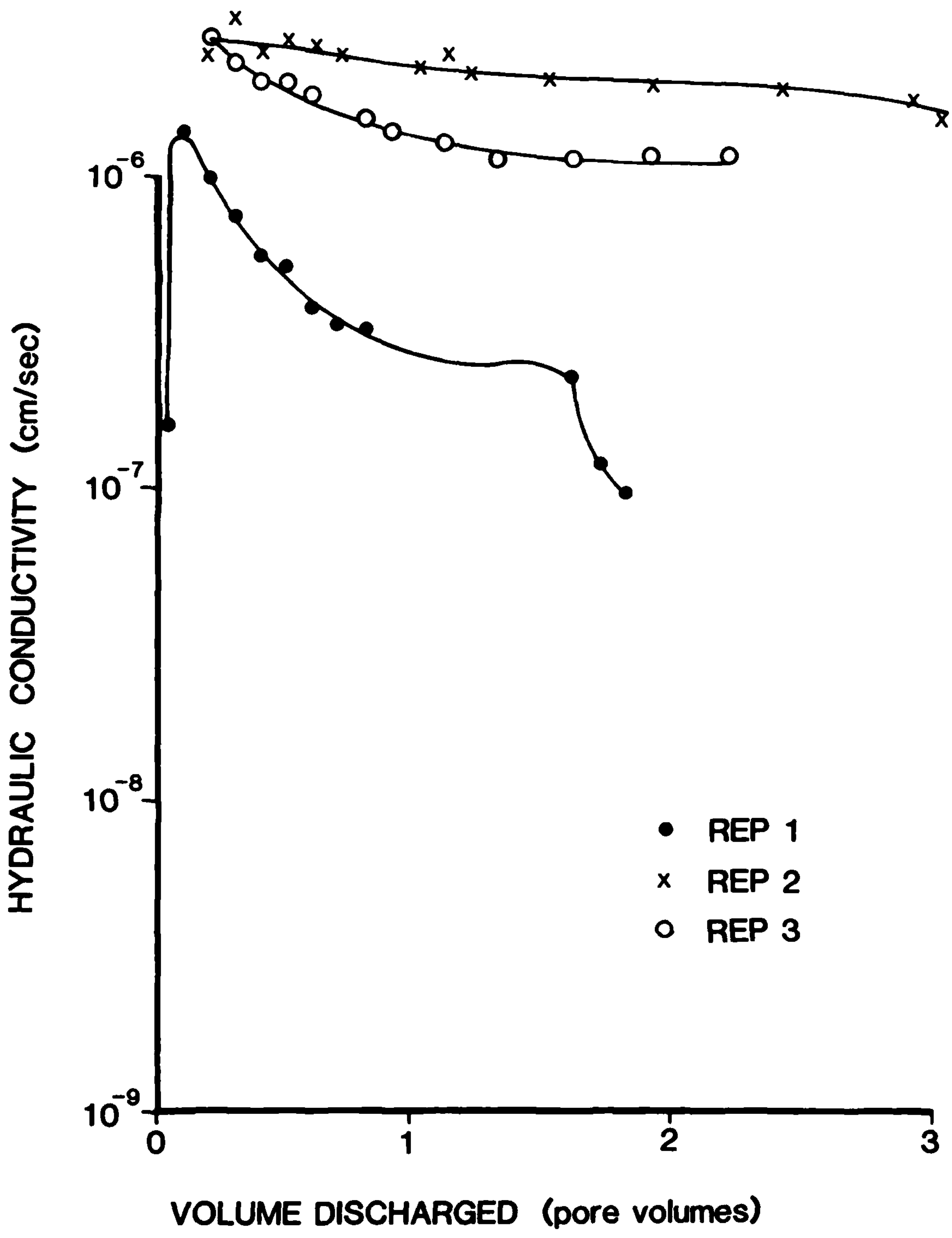

Figure 26. Hydraulic conductivity of unsaturated kaolinitic soil to 0.1% HNO_3 saturated with $Pb(NO_3)_2$

Figure 27. Print of radiograph of kaolinitic soil permeated with acidic lead nitrate solution, sectioned sample, actual size (Replicate 2)

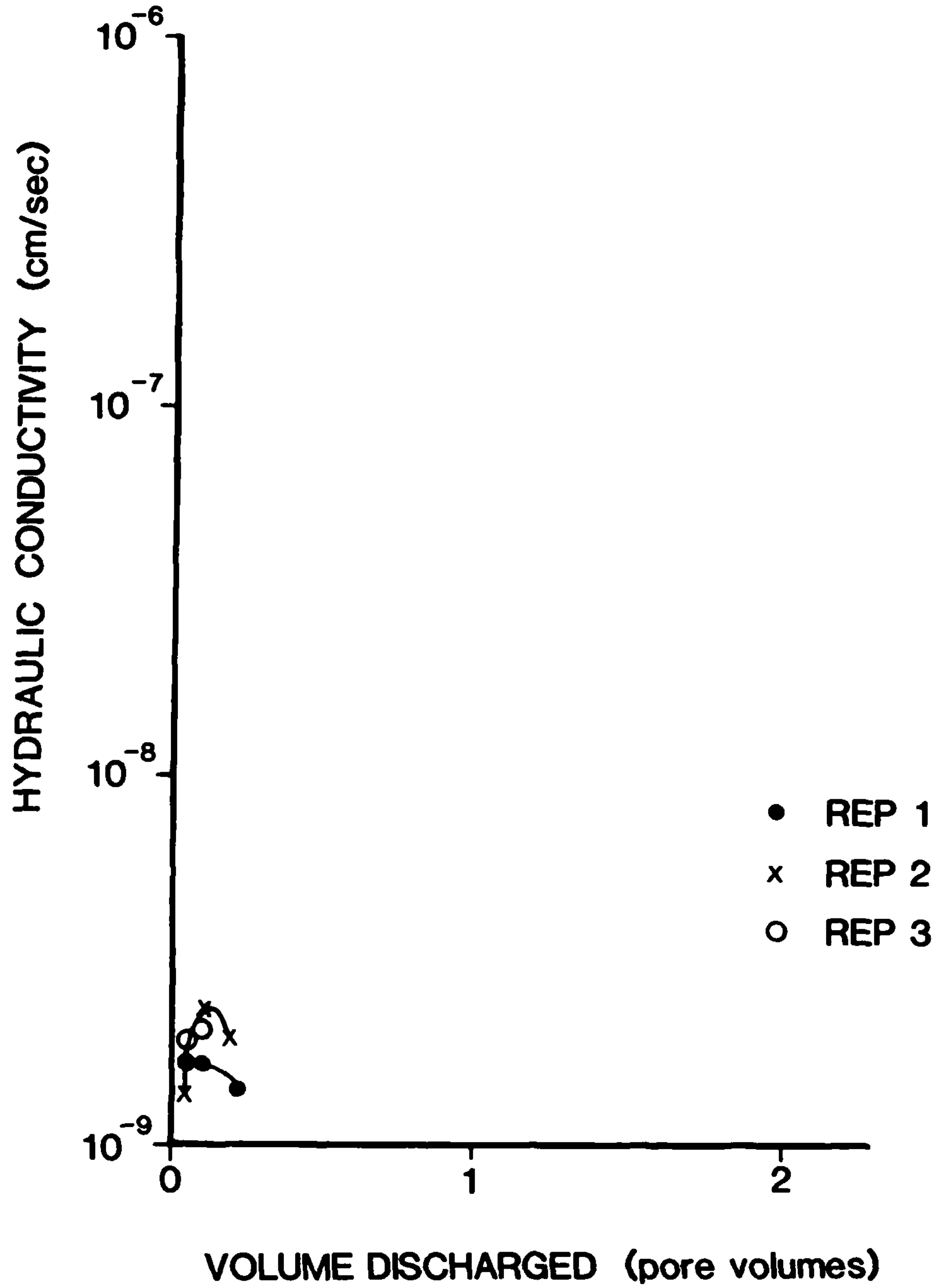

Figure 28. Hydraulic conductivity of unsaturated kaolinitic soil measured using acetone containing lead paint pigment at a gradient of 181

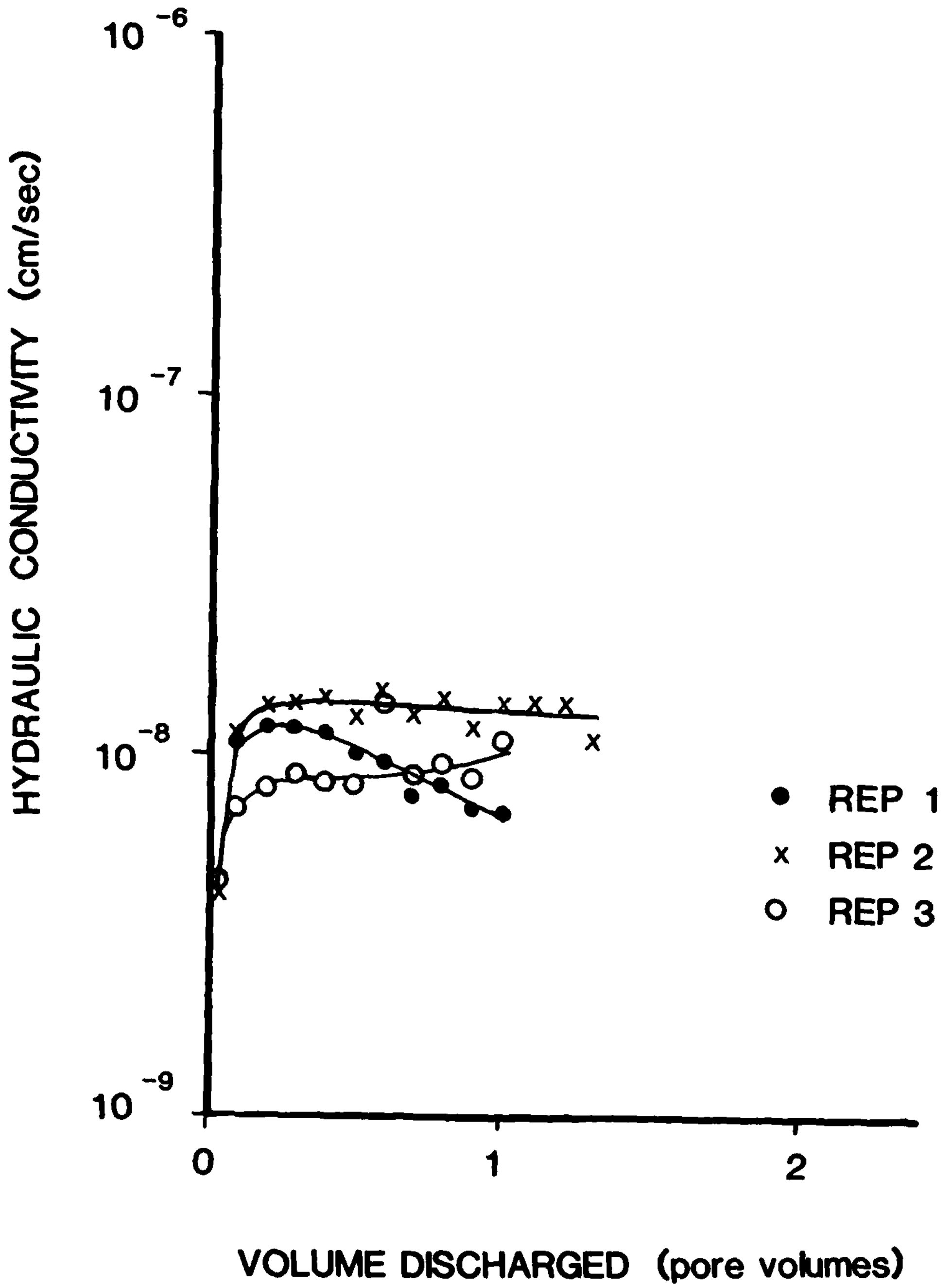

Figure 29. Hydraulic conductivity of unsaturated kaolinitic soil measured using xylene containing lead paint pigment

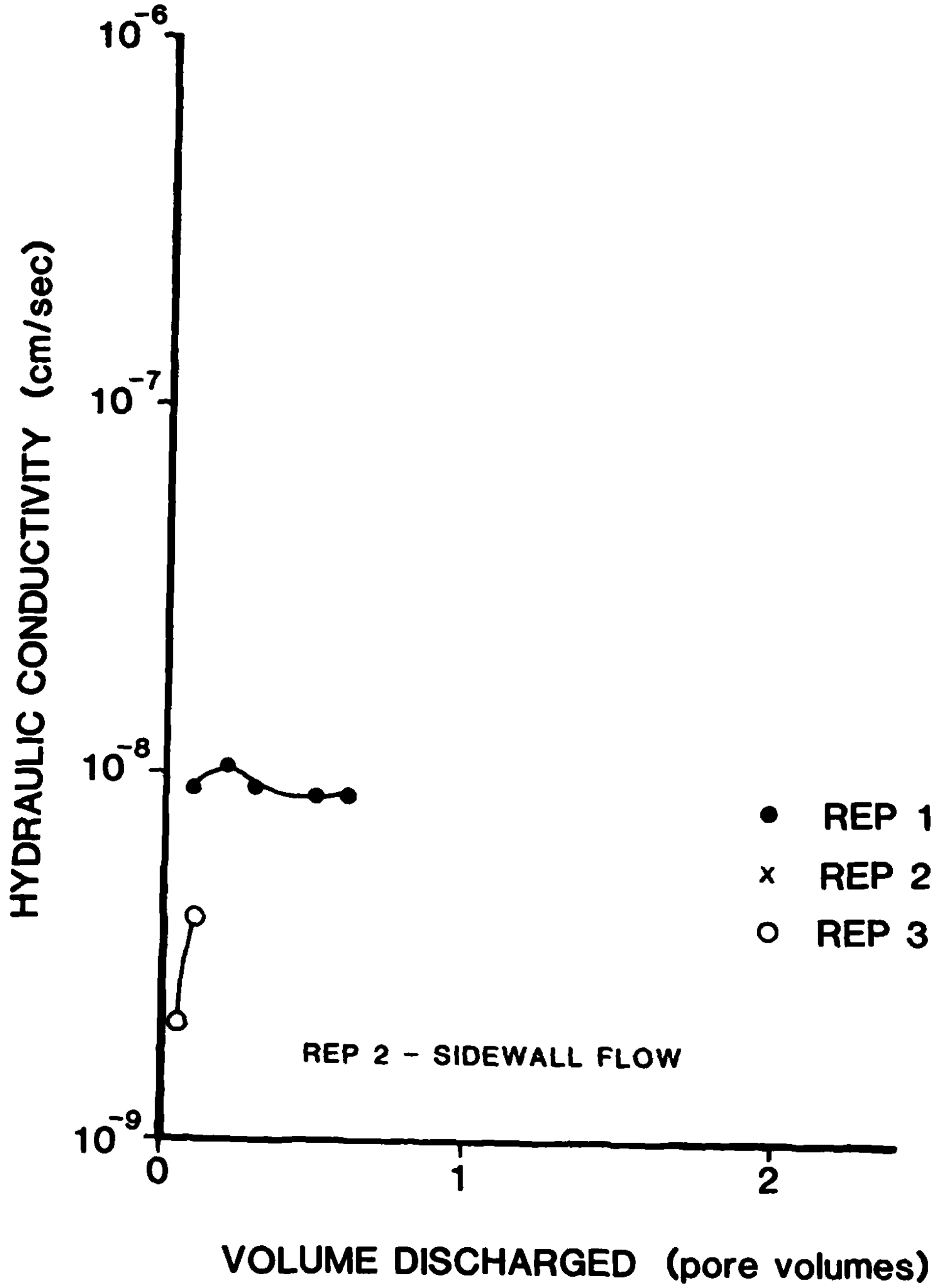

Figure 30. Hydraulic conductivity of unsaturated illitic soil measured using 0.01 N $CaSO_4$

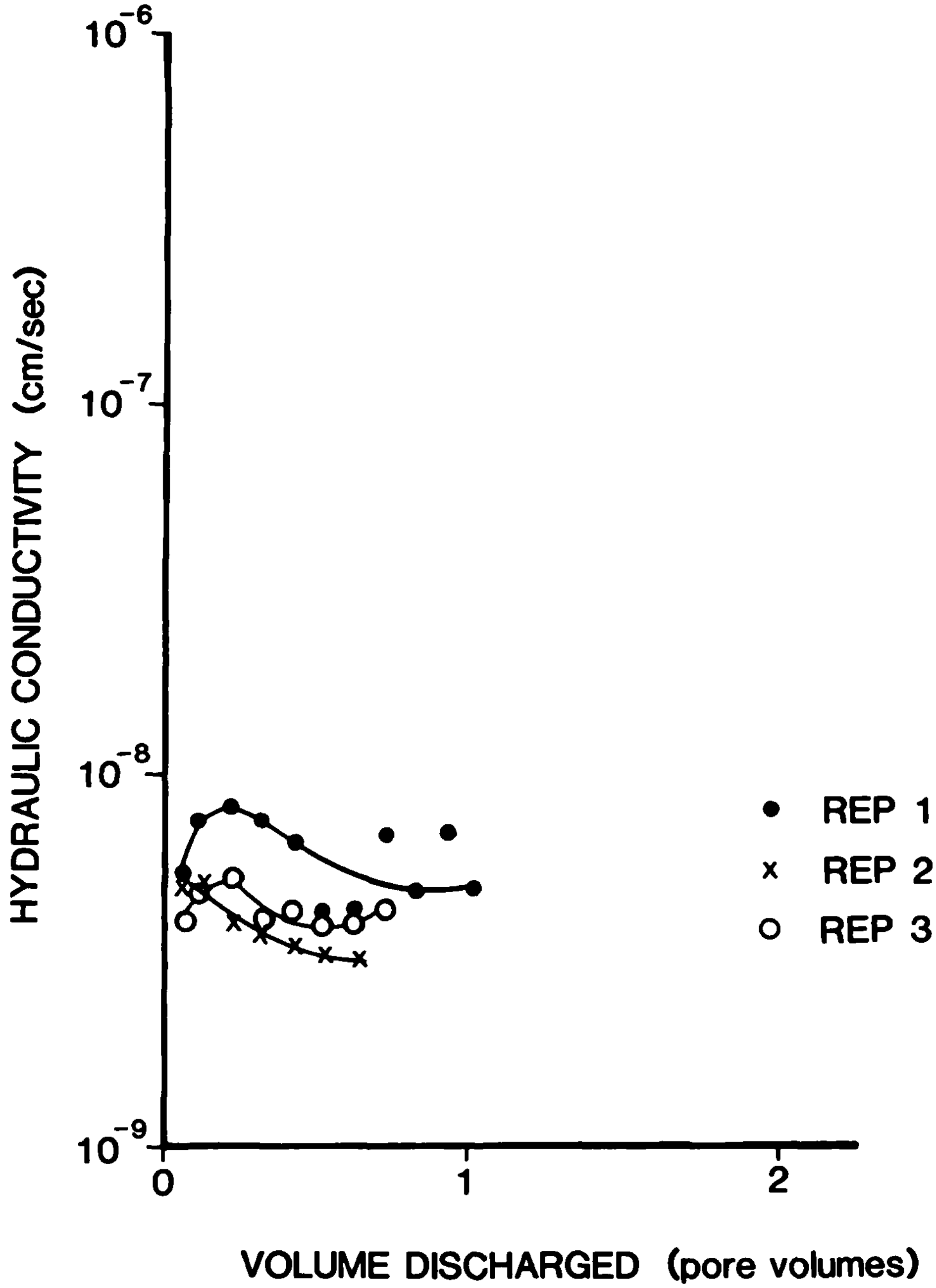

Figure 31. Hydraulic conductivities of unsaturated illitic soil measured using a saturated lead acetate solution

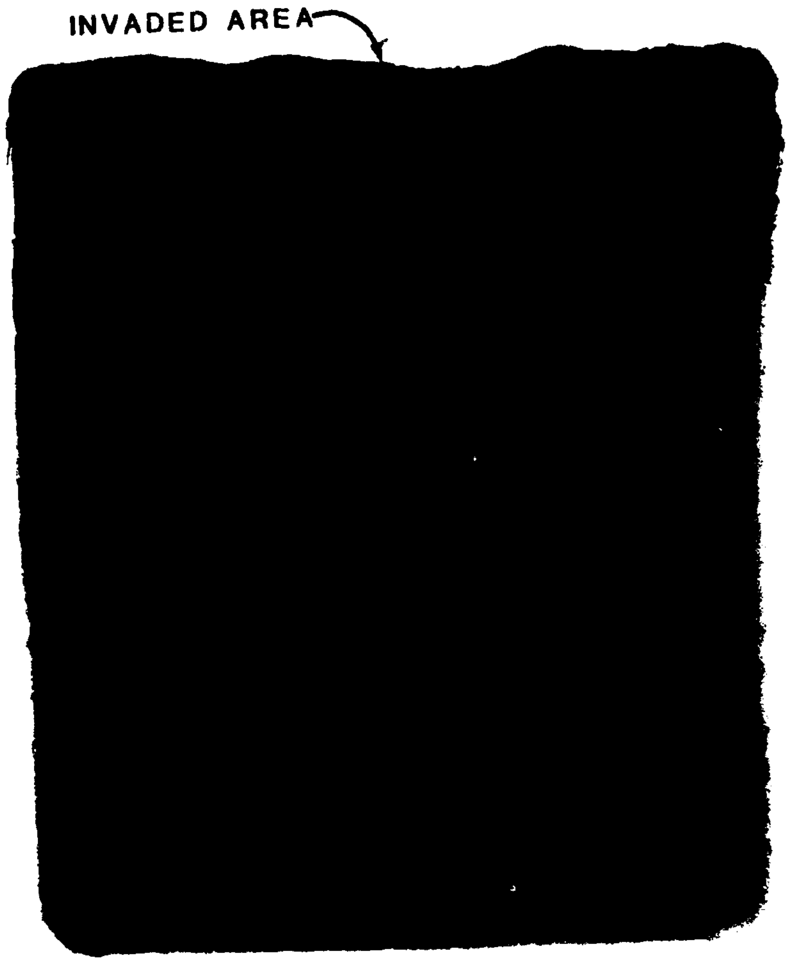

Figure 32. Print of radiograph of illitic soil permeated with lead acetate solution, whole sample, actual size (Replicate 1)

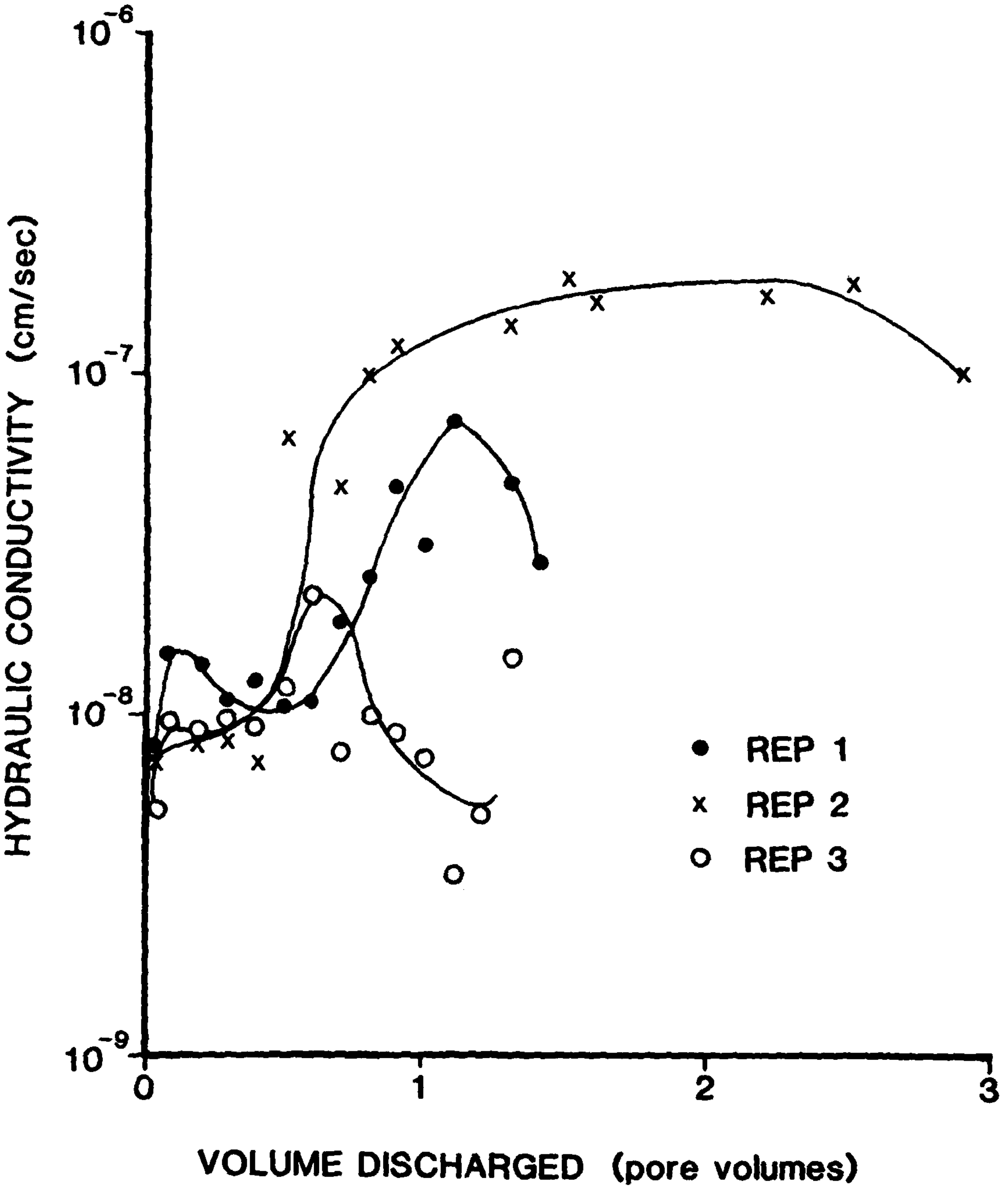

Figure 33. Hydraulic conductivity of unsaturated micaceous soil to 0.1% measured using HNO_3 saturated with $Pb(NO_3)_2$

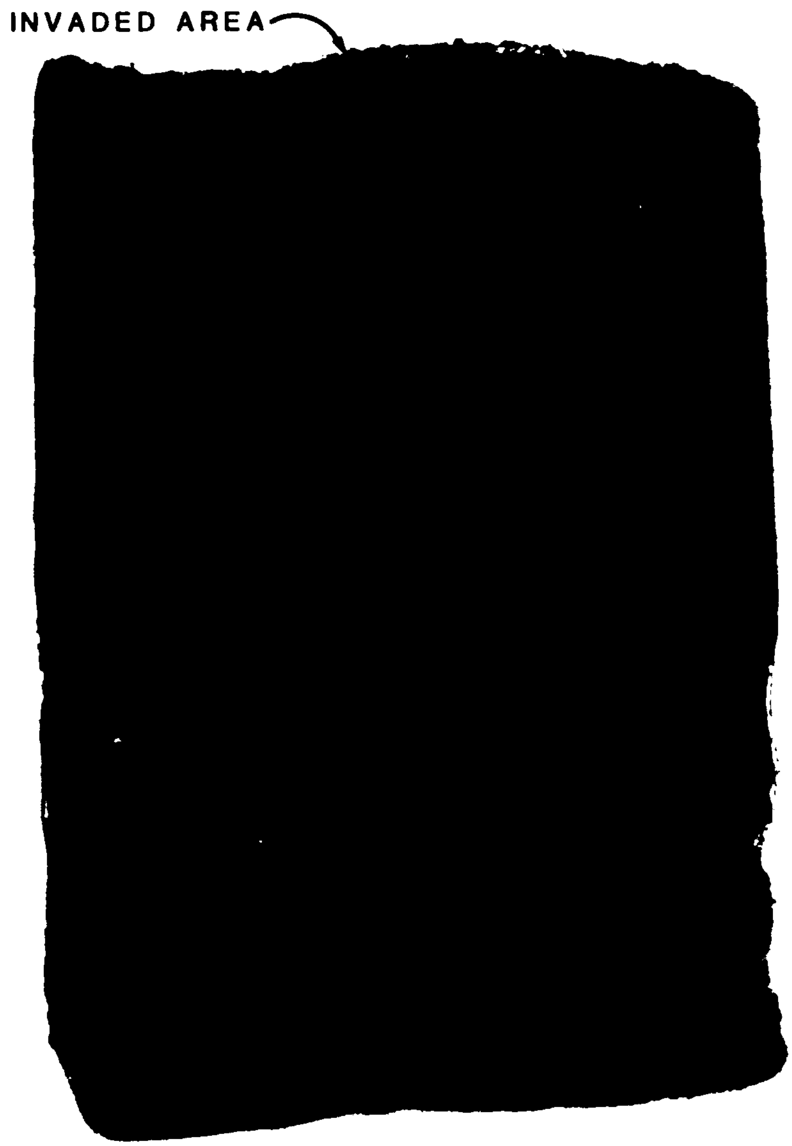

Figure 34. Print of radiograph of illitic soil permeated with acidic lead nitrate solution, section sample, actual size (Replicate 1)

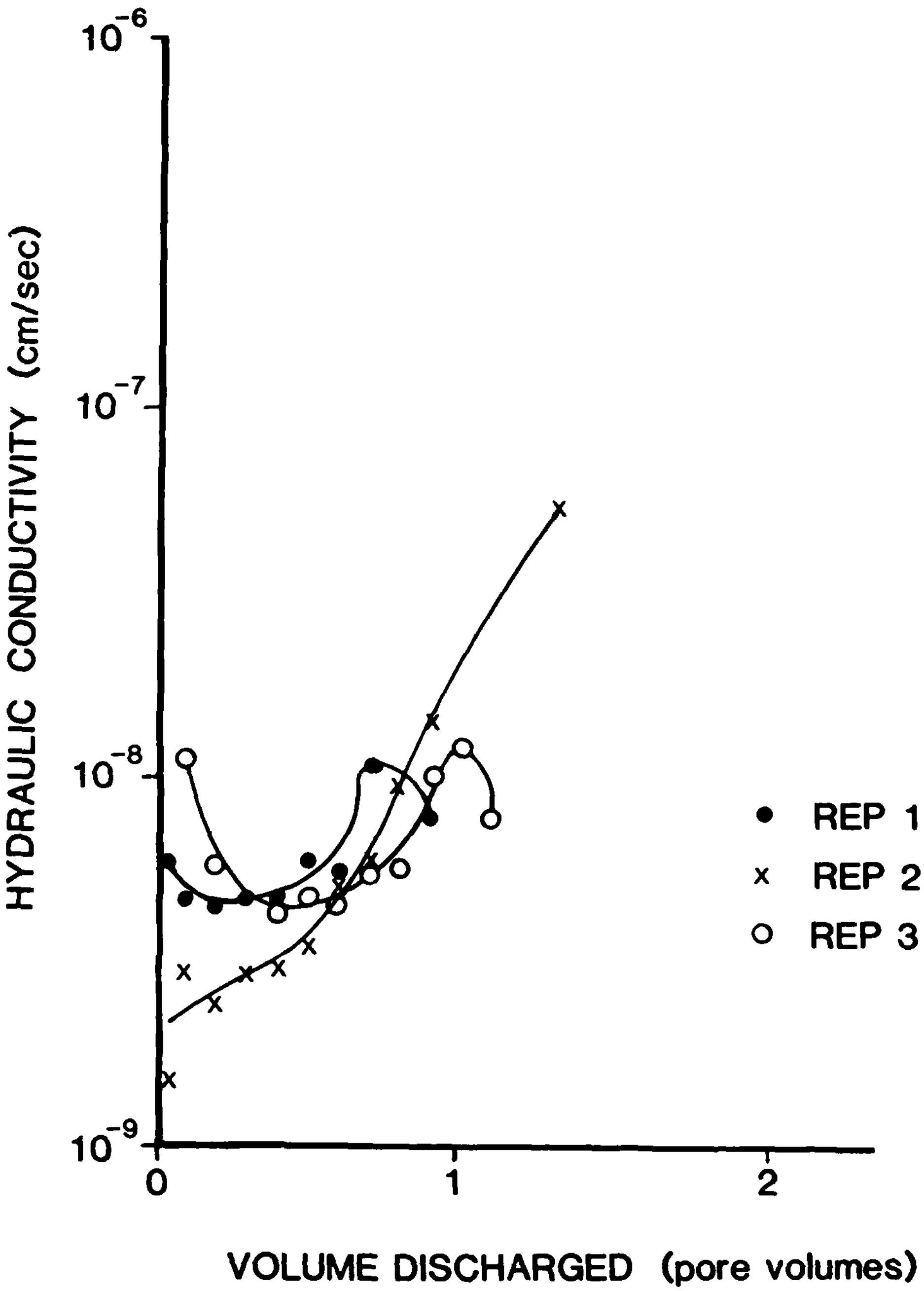

Figure 35. Hydraulic conductivity of unsaturated illitic soil measured using acetone containing lead paint pigment

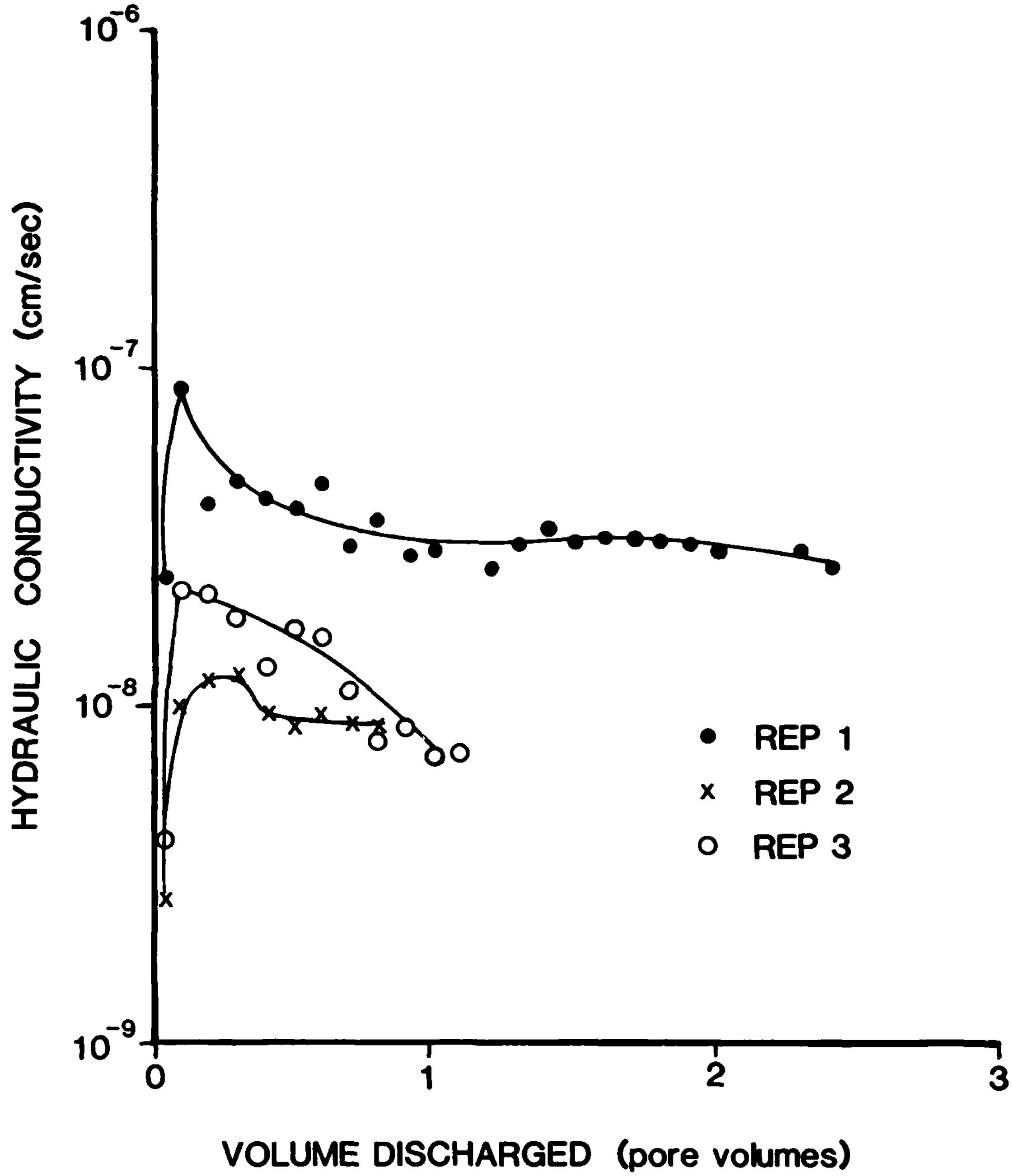

Figure 36. Hydraulic conductivity of unsaturated illitic soil measured using xylene containing lead paint pigment

35. X-ray examination often indicated that interaction between the liner and the liquid occurred when the permeability measurement showed little difference. For example, in the illitic soil, the hydraulic conductivities (Figures 30 and 31) recorded for the permeants, 0.01 N $CaSO_4$ and lead acetate are both low (near 10^{-8} cm/sec). The soil did, however, swell 1.5% (Table 4) when lead acetate was used as a permeant. X-ray examination of the sample shows that precipitation of lead had occurred through the entire top of the simulated liner (Figure 32) and more swelling could be expected if the precipitation continued. X-ray radiographs prepared during permeation are valuable for demonstrating liner changes but examination of sample after permeation is also helpful in confirming suspected changes or indicating interaction not evident from other measurements.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

36. X-radiography of soil samples can provide useful information on alteration in soil structure and on patterns of fluid penetration during hydraulic conductivity testing. X-ray examination of test samples offers numerous advantages:

- a. Voids or cracks produced by changes in soil structure can be readily identified.
- b. Local precipitation of waste constituents in the soil can be detected if the precipitates are dense enough to provide contrast in the X-ray.
- c. Changes in the liners which cannot be inferred from hydraulic conductivity measurements can be noted in X-rays.
- d. Non-uniform soil packing and permeant flow caused by leakage along the sidewall can be detected if the permeant contains soluble radio-opaque compounds.
- e. Inspection of samples using X-ray can be performed during permeation or on samples after hydraulic conductivity measurements are complete to provide verification of test performance.
- f. Simulated liners inspected during low-gradient experimental interaction with waste can be used to estimate the speed with which a particular type of waste can penetrate a liner.

Recommendations

37. Additional studies should be conducted with X-radiography to advance our techniques for laboratory-based liner testing and inspection of samples from waste sites. The studies should include:

- a. Fixed wall and triaxial hydraulic conductivity testing systems should be examined with X-ray while in operation to determine the extent and effect of problems with sample preparation and the effect of rigid or flexible sidewalls on fluid flow.
- b. X-ray examination should be applied to core samples from failed and properly functioning clay liner or slurry-wall materials to establish the extent and mode of failure.
- c. Liners containing lime or other buffering materials should be examined using X-ray techniques to demonstrate the effects of chemically reactive barriers in protecting liners.
- d. Organic-metal complexes (like tetraethyl lead) should be developed for use as tracers to obtain data on movement of organic wastes in liner materials.

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APPENDIX A

RESULTS OF PERMEABILITY TESTING

Table A1

Average Hydraulic Conductivity of Compacted Non-calcareous Smectite to 0.01 N $CaSO_4$

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
			<0.1	9.47E-8	0
			0.2	3.72E-8	
			0.3	2.54E-8	
0.4	1.34E-7	0.4	1.96E-8		
0.7	1.08E-7	0.5	1.91E-8		
0.8	7.06E-8	0.6	1.46E-8		
0.9	5.72E-8				
1.0	5.45E-8				
1.1	4.63E-8				

Table A2

Average Hydraulic Conductivity of Compacted Non-Calcareous Smectite to a Saturated Solution of Lead Acetate

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	1.28E-8	<0.1	1.12E-8	0.1	3.23E-8
0.1	1.67E-8	0.1	1.46E-8	0.2	2.27E-8
0.2	1.62E-8	0.2	1.47E-8	0.3	1.57E-8
0.3	8.51E-9	0.3	1.46E-8	0.4	2.69E-8
0.4	6.94E-9	0.4	1.21E-8	0.5	2.47E-8
0.5	6.22E-9	0.5	8.77E-9	0.6	2.28E-8
0.6	5.52E-9	0.6	5.72E-9	0.8	2.26E-8
0.7	5.66E-9	0.7	5.12E-9	0.9	2.37E-8
0.8	4.93E-9	0.8	6.00E-9	1.0	2.60E-8
0.9	5.52E-9	0.9	6.54E-9	1.1	2.35E-8
1.0	5.58E-9	1.0	6.98E-9	1.2	1.74E-8

Table A3

Average Hydrualic Conductivity of Compacted Non-Calcareous Smectite to 0.1% HNO_3 Saturated with $Pb(NO_3)_2$

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	1.18E-8	<0.1	6.83E-9	<0.1	3.84E-9
0.1	1.86E-8	0.1	1.15E-8	0.1	5.90E-9
0.2	1.89E-8	0.2	1.30E-8	0.2	7.46E-9
0.3	1.64E-7	0.3	1.79E-8	0.3	4.86E-8
0.4	2.08E-7	0.4	8.97E-9	0.8	5.82E-8
0.5	4.10E-8	0.5	9.74E-9	1.2	1.01E-7
0.6	5.52E-7	0.6	1.06E-8	1.3	1.12E-7
0.7	1.45E-6	0.7	1.41E-8		
1.2	1.60E-6	0.8	2.72E-8		
1.3	1.64E-6	0.9	2.29E-8		
1.4	1.66E-6	1.0	2.52E-8		
1.6	1.31E-6	1.1	2.40E-8		
		1.2	1.28E-8		

Table A4

Average Hydrualic Conductivity of Compacted Non-Calcareous Smectite to Acetone Containing Lead Paint Pigment

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	6.2E-10	0	0		

Table A5

Average Hydraulic Conductivity of Compacted Non-Calcareous Smectite to Xylene Containing Lead Paint Pigment

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	3.95E-9	<0.1	3.13E-8	<0.1	5.76E-9
0.1	2.27E-8	0.3	4.10E-8	0.1	1.03E-8
0.2	5.17E-8	0.4	3.17E-8	0.2	1.22E-8
0.3	3.47E-8	0.5	2.74E-8	0.3	1.18E-8
0.5	2.07E-8	0.6	2.24E-8	0.4	1.33E-8
0.6	1.70E-8	0.7	1.70E-8	0.5	1.18E-8
0.7	9.32E-9	0.8	1.53E-8	0.6	7.71E-9
0.8	9.48E-9	0.9	1.43E-8	0.7	5.65E-9
0.9	1.03E-8	1.0	9.23E-9	0.8	1.94E-9
1.0	9.19E-9	1.1	5.92E-9		

Table A6

Average Hydraulic Conductivity of Compacted Calcareous Smectite to 0.01 N $CaSO_4$ at a Gradient of 181

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	5.86E-9	<0.1	2.76E-7	0.1	8.02E-7
0.1	1.30E-8	0.3	2.39E-6	0.2	6.05E-7
0.2	1.62E-8	0.4	1.74E-6	0.3	4.61E-7
0.3	1.45E-8	0.7	1.29E-6	0.4	3.86E-7
0.4	1.38E-8	0.9	9.90E-7	0.9	2.18E-7
		1.0	4.78E-7	1.0	2.12E-7
		1.2	6.35E-7	1.1	1.74E-7
		1.3	2.99E-7	1.3	1.25E-7
		1.4	2.36E-7	1.4	4.47E-7
		1.5	5.85E-8		

Table A7

Average Hydraulic Conductivity of Compacted Calcareous Smectite to a Saturated Lead Acetate Solution

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
		0.1	1.27E-7	0.1	3.61E-7
0.2	1.50E-7	0.2	1.01E-7	0.2	3.97E-7
0.3	2.05E-7	0.3	5.04E-8	0.3	3.06E-7
0.4	1.49E-7	0.4	3.95E-8	0.6	1.03E-7
0.6	8.31E-8	0.5	3.77E-8	0.7	4.42E-8
0.8	6.37E-8	0.6	3.46E-8	0.9	4.26E-8
0.9	6.32E-8	0.7	3.02E-8	0.9	4.02E-8
1.1	5.71E-8			1.0	3.23E-8
1.2	4.18E-8				

Table A8

Average Hydraulic Conductivity of Compacted Calcareous Smectite to 0.1% HNO_3 saturated with $Pb(NO_3)_2$

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	2.26E-7				
0.1	2.69E-7			0.1	1.13E-7
0.3	1.44E-7			0.2	8.51E-7
0.4	1.09E-7	0.4	1.30E-6	0.3	1.46E-6
0.6	1.13E-7	0.5	1.50E-6	0.4	9.92E-7
0.7	1.65E-7	0.6	8.22E-7	0.5	7.04E-7
0.8	1.49E-7	0.7	9.62E-7	0.6	5.08E-7
1.0	1.22E-7	0.8	6.08E-7	0.7	2.17E-7
1.1	8.58E-8	0.9	4.15E-7		
1.2	7.58E-8	1.0	2.16E-7		

Table A9

Average Hydraulic Conductivity of Compacted Calcareous Smectite to Acetone Containing Lead Paint Pigment

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
0.1	1.95E-6	0.1	2.01E-8	0.00	0
0.2	4.73E-6	0.2	2.36E-6	0.00	0
0.3	5.14E-6			0.12	>6.57E-8
0.4	4.83E-6				
0.5	3.64E-6				
0.6	3.99E-6				
0.7	3.96E-6				
0.8	3.49E-6				
0.9	3.30E-6				

Table A10

Average Hydraulic Conductivity of Compacted Calcareous Smectite to Xylene Containing Lead Paint Pigment

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	3.09E-8	<0.1	1.53E-8	<0.1	1.88E-9
0.1	3.94E-8	0.1	2.23E-8	0.1	4.27E-8
0.2	3.53E-8	0.2	2.33E-8	0.2	3.66E-8
0.3	2.36E-8	0.3	1.57E-8	0.4	1.88E-8
0.4	2.87E-8	0.4	1.44E-8	0.5	1.30E-8
0.5	1.64E-8	0.5	1.64E-8	0.6	9.61E-9
0.6	1.17E-9	0.6	9.62E-9	0.7	4.83E-9
0.7	5.01E-9	0.7	8.39E-9	0.8	2.98E-9
0.8	1.77E-9	0.8	8.25E-9	0.9	1.61E-9
		0.9	5.45E-9		
		1.0	5.57E-9		

Table A11

Average Hydraulic Conductivity of Compacted Illitic Soil to 0.01 N $CaSO_4$

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
				<0.1	2.11E-9
0.1	9.20E-9	0.00	0	0.1	3.96E-9
0.2	1.05E-8	1.80	<2.66E-7		
0.3	9.21E-9				
0.5	8.72E-09				
0.6	8.92E-9				

Table A12

Average Hydraulic Conductivity of Compacted Illitic Soil to a Saturated Lead Acetate Solution

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	5.17E-9	<0.1	5.01E-9	<0.1	3.95E-9
0.1	7.30E-9	0.1	4.87E-9	0.1	4.71E-9
0.2	8.02E-9	0.2	4.00E-9	0.2	5.15E-9
0.3	7.27E-9	0.3	3.78E-9	0.3	4.04E-9
0.4	6.58E-9	0.4	3.36E-9	0.4	4.31E-9
0.5	4.16E-9	0.5	3.32E-9	0.5	3.85E-9
0.6	4.25E-9	0.6	3.15E-9	0.6	4.04E-9
0.7	6.92E-9			0.7	4.45E-9
0.8	4.85E-9				
0.9	6.81E-9				
1.0	4.73E-9				

Table A13

Average Hydraulic Conductivity of Compacted Illitic Soil to 0.1% HNO_3 Saturated with $Pb(NO_3)_2$

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	8.14E-9	<.1	7.95E-9	<0.1	5.43E-9
0.1	1.46E-8	0.1	9.62E-9	0.1	9.38E-9
0.2	1.40E-8	0.2	8.36E-9	0.2	9.03E-9
0.3	1.12E-8	0.3	8.35E-9	0.3	9.84E-9
0.4	1.24E-8	0.4	7.00E-9	0.4	9.14E-9
0.5	1.07E-8	0.5	6.42E-8	0.5	1.28E-8
0.6	1.10E-8	0.7	4.66E-8	0.6	2.34E-8
0.7	1.92E-8	0.8	1.04E-7	0.7	7.76E-9
0.8	2.55E-8	0.9	1.21E-7	0.8	1.04E-8
0.9	4.70E-8	1.3	1.40E-7	0.9	8.87E-9
1.0	3.15E-8	1.5	1.88E-7	1.0	7.55E-9
1.1	7.14E-8	1.6	1.64E-7	1.1	3.40E-9
1.3	4.65E-8	2.2	1.70E-7	1.2	5.04E-9
1.4	2.73E-8	2.5	1.87E-7	1.3	1.49E-8
		2.9	1.00E-7		

Table A14

Average Hydraulic Conductivity of Compacted Illitic Soil to Acetone Containing Lead Paint Pigment

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	5.94E-9	<0.1	1.51E-9		
0.1	4.57E-9	0.1	2.90E-9	0.1	1.13E-8
0.2	4.41E-9	0.2	2.41E-9	0.2	5.72E-9
0.3	4.59E-9	0.3	2.90E-9	0.3	4.65E-9
0.4	4.70E-9	0.4	2.96E-9	0.4	4.22E-9
0.5	5.92E-9	0.5	3.38E-9	0.5	4.72E-9
0.6	5.47E-9	0.6	4.96E-9	0.6	4.51E-9
0.7	1.10E-8	0.7	5.77E-9	0.7	5.40E-9
0.8	9.70E-9	0.8	9.56E-9	0.8	5.73E-9
0.9	7.80E-9	0.9	1.45E-8	0.9	1.00E-8
		1.3	5.23E-8	1.0	1.16E-8
				1.1	7.68E-9

Table A15

Average Hydraulic Conductivity of Compacted Illitic Soil to Xylene Containing Lead Paint Pigment

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	2.39E-8	<0.1	2.71E-9	<0.1	4.04E-9
0.1	8.66E-8	0.1	1.04E-8	0.1	2.19E-8
0.2	4.03E-8	0.2	1.22E-8	0.2	2.12E-8
0.3	4.60E-8	0.3	1.25E-8	0.3	1.76E-8
0.4	4.07E-8	0.4	9.52E-9	0.4	1.28E-8
0.5	3.81E-8	0.5	8.89E-9	0.5	1.68E-8
0.6	4.49E-8	0.6	9.27E-9	0.6	1.65E-8
0.7	2.98E-8	0.7	8.87E-9	0.7	1.11E-8
0.8	3.50E-8	0.8	8.71E-9	0.8	7.89E-9
0.9	2.82E-8			0.9	8.69E-9
1.0	2.86E-8			1.0	7.16E-9
1.2	2.64E-8			1.1	7.40E-9
1.3	3.14E-8				
1.4	3.41E-8				
1.5	3.07E-8				
1.6	3.21E-8				
1.7	3.18E-8				
1.8	3.11E-8				
1.9	3.07E-8				
2.0	2.86E-8				
2.3	2.87E-8				
2.4	2.59E-8				

Table A16

Average Hydraulic Conductivity of Compacted Kaolinitic Soil to 0.01 N $CaSO_4$

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
2.0	2.51E-7	0.2	4.84E-8		
0.3	2.87E-7	0.3	2.09E-7	0.4	3.97E-7
0.8	1.59E-7	0.5	1.85E-8	0.5	2.66E-7
0.9	9.32E-8	0.6	6.04E-9	1.0	1.56E-7
1.0	1.48E-8	0.7	5.38E-9	1.1	1.21E-7
1.1	1.76E-9			1.2	1.02E-7
				1.4	8.90E-8
				1.5	6.04E-8

Table A17

Average Hydraulic Conductivity of Compacted Kaolinitic Soil to Saturated Lead Acetate Solution

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
0.6	1.73E-7	0.2	4.90E-8	0.4	9.97E-8
1.0	7.15E-8	0.3	8.75E-9	0.8	9.26E-8
1.3	5.17E-8	0.4	3.77E-9	1.2	5.85E-8
1.5	4.53E-8	0.5	2.6E-10	1.3	3.87E-8
1.6	4.15E-8	0.7	5.42E-7	1.4	3.10E-8
		1.1	1.23E-7		
		1.2	1.01E-7		
		1.5	7.16E-8		
		1.6	9.32E-8		

Table A18

Average Hydraulic Conductivity of Compacted Kaolinitic Soil to 0.1% HNO_3 Saturated with $Pb(NO_3)_2$

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	1.64E-7				
0.1	1.43E-6				
0.2	9.94E-7	0.2	2.55E-6	0.2	2.85E-6
0.3	7.57E-7	0.3	3.82E-6	0.3	2.29E-6
0.4	5.67E-7	0.4	2.45E-6	0.4	2.03E-6
0.5	5.19E-7	0.5	2.73E-6	0.5	1.97E-6
0.6	3.79E-7	0.6	2.65E-6	0.6	1.82E-6
0.7	3.36E-7	0.7	2.49E-6	0.8	1.55E-6
0.8	3.41E-7	1.0	2.27E-6	0.9	1.37E-6
1.6	2.43E-7	1.1	2.49E-6	1.1	1.32E-6
1.7	1.22E-7	1.2	2.18E-6	1.3	1.16E-6
1.8	9.94E-8	1.5	2.11E-6	1.6	1.15E-6
		1.9	2.03E-6	1.9	1.23E-6
		2.4	1.98E-6	2.2	1.18E-6
		2.9	1.82E-6		
		3.0	1.64E-7		

Table A19

Average Hydraulic Conductivity of Compacted Kaolinitic Soil to Acetone Containing Lead Paint Pigment

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	1.65E-9	<0.1	1.28E-9	<0.1	1.90E-9
0.1	1.62E-9	0.1	2.22E-9	0.1	2.03E-9
0.2	1.39E-9	0.2	1.94E-9		

Table A20

Average Hydrualic Conductivity of Compacted Kaolinitic Soil to Xylene Containing Lead Paint Pigment

Replicate 1		Replicate 2		Replicate 3	
Pore Volume	Ave K	Pore Volume	Ave K	Pore Volume	Ave K
<0.1	4.21E-9	<0.1	4.16E-9	<0.1	4.40E-9
0.1	1.08E-8	0.1	1.13E-8	0.1	7.07E-9
0.2	1.19E-8	0.2	1.38E-8	0.2	8.14E-9
0.3	1.18E-8	0.3	1.38E-8	0.3	8.71E-9
0.4	1.16E-8	0.4	1.45E-8	0.4	8.28E-9
0.5	1.03E-8	0.5	1.30E-8	0.5	8.16E-9
0.6	9.66E-9	0.6	1.51E-8	0.6	1.38E-8
0.7	7.83E-9	0.7	1.31E-8	0.7	8.98E-9
0.8	8.36E-9	0.8	1.46E-8	0.8	9.51E-9
0.9	7.12E-9	0.9	1.19E-8	0.9	8.73E-9
1.0	7.00E-9	1.0	1.36E-8	1.0	1.16E-8
		1.1	1.42E-8		
		1.2	1.43E-8		
		1.3	1.07E-8		

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